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A phenomenographic study of the ability to address complex socio-technical systems via variation theory

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A PHENOMENOGRAPHIC STUDY OF THE ABILITY TO ADDRESS COMPLEX SOCIO-TECHNICAL SYSTEMS VIA VARIATION THEORY

A Dissertation

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of

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John A. Mendoza Garcia

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A mi amada y valiente amiga, compañera y esposa, Andrea y a mi maestra del amor, quien le da luz y sentido a mi vida, mi hija Isabella.

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ABSTRACT

Mendoza Garcia, John A. Ph.D., Purdue University, August 2016. A Phenomenographic Study of the Ability to Address Socio-Technical Systems via Variation Theory. Major Professors: Monica E. Cardella, William C. Oakes. School of Engineering Education

Sometimes engineers fail when addressing the inherent complexity of socio-technical systems because they lack the ability to address the complexity of socio-technical systems.

Teaching undergraduate engineering students how to address the complexity of socio-technical systems, an ability that is also called systems thinking, has been an educational endeavor at different levels ranging from kindergarten to post-graduate education. The literature presents different pedagogical strategies and content to reach this goal. However, there are no existing empirically-based assessments guided by a learning theory. This may be because at the same time explanations of how the skill is developed are scarce.

My study bridges this gap, and I propose a developmental path for the ability to address the complexity of socio-technical systems via Variation Theory. This theory explains that the awareness of the object of learning can be described in terms of critical aspects or dimensions of variation, and critical features within that dimension. Accordingly, people learn because they are able to open a new dimension of variation, or learn a new value or feature within a dimension. In other words, they achieve a higher

awareness of the object of learning. A way of experiencing the awareness of the object of learning is then composed by a set of critical aspects and critical features. Accordingly, my research question is “What are the various ways in which engineers address complex socio-technical systems?”

I chose the research approach of phenomenography to answer my research question. I also chose to use a blended approach, Marton’s approach for finding the dimensions of variation, and the developmental approach (Australian) for finding a hierarchical relationship between the dimensions. Accordingly, I recruited 25 participants with different levels of experience with addressing complex socio-technical systems and asked them all to address the same two tasks: A design of a system for a county, and a case study in a manufacturing firm.

My outcome space is a nona-dimensional (nine) developmental path for the ability to address the complexity in socio-technical systems, and I propose 9 different ways of experiencing the complexity of a socio-technical system.

The findings of this study suggest that the critical aspects that are needed to address the complexity of socio-technical systems are: being aware of the use of models, the ecosystem around, start recognizing different boundaries, being aware of time as a factor, recognizing the part-whole relationships, make effort in tailoring a solution that responds to stakeholders’ needs, find the right problem, giving voice to others, and finally be aware of the need to iterate.

CHAPTER 1. INTRODUCTION[1]

1.1 The Need to Develop Systems Thinking

The engineering design error in the New Orleans levees (Marris, 2005), the billions of dollars lost in large engineering projects that have failed (Bar-Yam, 2003), environmental catastrophes such as the desiccation of the Aral Sea (Micklin, 2007) are just few examples that show that sometimes engineers failed when addressing complex socio-technical systems.

New Orleans's case was explained by Levin (2006) who cited the Army Corps of Engineers:

> New Orleans' levees failed during Hurricane Katrina because federal engineers for decades did not anticipate the potential height of storm waters and underestimated the strength required to hold them back … [The corps also said:] A well-designed levee system might not have held back the high waves and storm surge that swamped nearly 80% of New Orleans and vast areas nearby, but it would have minimized damage and allowed a swifter recovery …

Levin also mentioned that according to tests performed in the 1980's, "the levees could crumble under pressure from high water" and that "those findings were not used in the

[1] A preliminary version of the first three chapters of this dissertation were published in Mendoza-Garcia J., Cardella M., Oakes W. Various ways of experiencing dealing with complex problems. Frontiers in Education. Madrid, España. © 2014 IEEE. The paper is available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7044347&tag=1

design”. However, beyond this finding of the fail in the design, what is remarkable is the comment made by engineers from the University of California-Berkeley in which they stated that the corps received political pressure and have organizational problems that impacted the engineering work. This finding from the University of California-Berkeley makes evident that the complexity of an engineering problem goes beyond the technology required to address it, and has to include strategies to deal also with its inherent social system.

In regards of the large engineering projects cited by Bar-Yam (2003), the author cited a failed project aiming to redesign of an air traffic control system. He mentioned that the failure was attributed to the U.S. government procurement process involving the FAA and the congress. Additionally, there were failures, among others, in the definition of the project specifications/requirements, the short estimated time in changing from the old system to the new one, and because of the “safety veto” exercised by air traffic controllers who were concerned about the safety provided by the new system. This example shows that the complexity goes beyond the technical components of the system and engineers must go beyond the technical sphere if their goal is to succeed in the design of large scale technological systems.

The last example I cited as engineering failure is the desiccation of the Aral sea (Micklin, 2007). According to the author, the water from its two tributary rivers was extracted for human consumption, and especially to attend the agricultural demands of the famers who were close to the river. Although the irrigation systems were becoming more efficient, it expanded and with the time, the water in the rivers was not enough to fill the Aral Sea basin. In this case, what the socio-technical system there, lack to consider was the impact of their actions in the long term, and it looks like the engineers who were part of it, creating the irrigation systems, did not contribute on facilitating others to make this consideration.

Engineering failures have motivated engineering professional societies, National Academy of Engineering (2004), the National Science Board (2007), experts like Duderstadt (2008) and Vest (2008), engineering education academics from institutions like the Carnegie Foundation (2009), and engineering education researchers like me (Mendoza-Garcia et al., 2012) to argue that undergraduate engineering programs should go beyond teaching engineering fundamentals, and they should also consider developing high order thinking skills (Edwards & Briers, 2000).

High order thinking skills will allow engineering graduates to be ready to address the real-world complexity. These authors also agree to say that current curricula are not sufficient to prepare engineering students for the current challenges of professional practice and engineering schools are also worried about graduates inability to address the current and future complexity of the real-world when designing engineering artifacts that intend to solve needs of real customers (National Academy of Engineering, 2008). What is interesting is that systems thinking has been taught in different engineering schools which shows their awareness of this need.(Cavaleri & Sterman, 1997; Sosa, Dorantes, & Cárdenas, 2010; L. B. Sweeney & Sterman, 2007; Witjes, Montoya Rodriguez, & Specht, Muñoz, 2006).

Complexity increases in a system as the number of components, its relationships, and its interactions also increase, and as result, the system develops new emergent properties and behaviors that cannot be seen in the short-term (Bertoglio & Johansen, 1982; Capra, 1996). As we can infer from above, engineering failures happened in part because engineers focused their attention in managing the increasing number of technological components the system could have, which makes it more complicated (Grabowski & Strzalka, 2008), but oversaw the social and the environmental components that makes them complex.

Developing the ability to address the complexity of socio-technical systems has become a crucial skill when engineers engineer systems. For example, the International Council of Systems Engineering - INCOSE, aware of this need, aims in its 2025 vision the promotion of the teaching of systems engineering knowledge across all engineering fields and even in k-12 education (INCOSE, 2014). This is because they believe that systems engineering knowledge will equip engineers with powerful cognitive tools to address this complexity. Some authors have matched this ability to address complexity with systems thinking, while others have made it part of the ability. For example, INCOSE includes systems thinking in the systems engineering knowledge, but also includes the need for leadership, socio-technical and domain-specific knowledge when engineering systems. Other authors have asked for development of systems related thinking for addressing complexity as well. For example, Sosa, Dorantes & Cárdenas called for "systemic thinking" to succeed in sustainable design (2010); Stasinopoulos (2008) asked for long-term thinking when engineering sustainable solutions; Checkland (1981), Senge (1990), and Sterman (1994; 2001) argued that "systems thinking" is necessary when understanding and transforming socio-technical systems such as organizations, or when designing public policies.

We can also infer that if students learn to address complexity of socio-technical systems, our programs will be able to say their students are achieving the following outcomes for student learning (ABET, 2015):

- “design … to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability”.
- “understanding professional and ethical responsibility”
- Develop the “ability … to understand the impact of engineering solutions in a global, economic, environmental, and societal context”

In the following section you will find the development of the problem formulation for this study in regards of the gap of knowledge regarding the development of systems thinking, or the ability to address the complexity of socio-technical systems.

1.2 Developing Systems Thinking in formal academic environments

Different attempts to teach or develop systems thinking have been conducted in educational levels that have ranged from kindergarten to post-graduate education (Draper, 1993; Megan Hopper, 2007; Sterman, 1994; L. B. Sweeney & Sterman, 2007). In fact, Hooper & Stave (2008) found 200 publications in which interventions in the classroom were seeking to determine or increase learners’ levels of systems thinking. However, learning experiences in schooling environments are not perceived as critical to developing systems thinking, as was found by Davidz (2006) in her study with more than 200 systems engineers whose majority did not perceive academic experiences as key enablers of their systems thinking ability. Accordingly, it is plausible to think that the learning outcomes engineering programs have regarding the development of systems thinking are not completely achieved in our current engineering school system if people do not perceive the value of these formal learning experiences in the development of that particular skill. Additionally, there is also a potential that these participants did not developed the ability itself at the moment of instruction, but later in other informal learning environments, and that is why they do not see connection between the formal learning environment and the development of this skill.

According to Streveler and her colleagues, a possible reason that may explain why systems thinking learning outcomes are not reached is a lack of alignment between content, assessment and pedagogy (Streveler, Smith, & Pilotte, 2012). A crucial component in this content-assessment-pedagogy triangle (a metaphor that is used to show the need of alignment between the three) is the knowledge of how the learners develop knowledge of the object of learning. For example, effective teaching requires knowing what content could move forward student's understanding of the object of learning, and at the same time, that instructors should be able to recognize where their students are, so they can adapt their instruction to move them forward in that developmental path (Marton, 2014; Pellegrino, 2002).

Teaching experiences promoting systems thinking development such as those reported by Hooper & Stave (2008), show advances on content and delivery. However, assessment that facilitates diagnosis of students' current ability to deal with problem in complex systems was, according to them, still not standard and was based on subjective perceptions (Davidz, 2006; Hooper & Stave, 2008), which does not respond to the need of alignment between the three curricular components. Assessment that responds to that need requires to be designed also aligning the assessment task, the interpretation for what the learner produces as a response to the task, with the learning theories that explained how the learning of the subject is developed.

Theories that explain the development of systems thinking are scarce. Davidz (2006) explained that it was necessary to assess the quality of systems thinking and to do that, it was a need to do more "work … to first understand the development of systems thinking at an individual level of analysis" (2006, p. 46). Lamb (2009), who cited Davidz's work, stated that the question about the development of systems thinking remained unresolved.

Searches in two databases that index engineering educational research publications (Compendex and Inspec), and another in the educational database ERIC were conducted in June 2016 to see if new papers on the development of systems thinking after Lamb's research study were published (see details in Table 1.1).

Table 1.1 - Database searchers for systems thinking development in the last 5 years

Database	Search string	Number of Hits
Compendex & Inspec	(((("development of systems thinking" OR "systems thinking development"))) AND ((2015 OR 2014 OR 2013 OR 2012 OR 2011) WN YR))	9
ERIC	("development of systems thinking" OR "systems thinking development")	3

The search in Compendex and Inspec using just the terms "development of systems thinking" OR "systems thinking development" retrieved 9 papers. One of these was this dissertation proposal (Mendoza-Garcia, Cardella, & Oakes, 2014), which decreased the number to 8.

These searches found two studies co-authored by Kordova and Frank, regarding the development of what they called the Engineering Capacity for Systems Thinking

(ECST), which according to them, is what is needed to address complexity in complex systems(S Koral Kordova & Frank, 2015; Sigal Koral Kordova, Ribnikov, & Frank., 2015).

However, it is relevant to say here that these two papers are the same paper, published in two different conferences with a different title. In that study, they measure students' ECST before a capstone project, and after it, and find an increase in their ECST. However, they do not explain why the intervention works, and how it contributed to develop the skill. I will be back to their measurement model in chapter two, and I will show you the fundamental flaws I found in it.

Regarding the other papers found in compendex and ERIC, the search discusses methods for systems thinking development such as gaming (Fabricatore & Lopez, 2012; Fabricatore, 2011), or team work (Moser, Ziegler, Blessing, & Braukhane, 2012) or include systems thinking development as part of the learning of science (Vachliotis, Salta, Vasiliou, & Tzougraki, 2011), which is different to my scope regarding the addressing of complex socio-technical systems. The final paper provided an overview of organizational theories in which one of the key components of these theories is systems thinking, but still, do not proposed theories regarding its development (Syme, Bennett, MacPherson, & Thomas, 2011).

1.3 Purpose of the Study

The purpose of this study is to contribute to close the gap of knowledge regarding a descriptive path for the ability to address complex systems.

Filling this gap will contribute to engineering education because there is an urgent call from professionals and the academic engineering community (among other communities) to support our students in the development of the ability to address complexity (ABET, 2015; ASEE, 2012; Duderstadt, 2008; National Academy of Engineering, 2004; Sheppard et al., 2009; Vest, 2008). Additionally, the ability to address complexity, or systems thinking, is a topic that has been taught for several years from kindergarten to postgraduate levels in several disciplines. In engineering there are examples of courses in systems engineering (Cavaleri & Sterman, 1997; Frank & Elata, 2005; L. Sweeney & Sterman, 2001), environmental engineering (Megan Hopper, 2007), sustainable engineering (Cardenas & Sosa, 2010; Gulwadi, 2009; Nikou, n.d.; Sosa et al., 2010; Stasinopoulos, 2008), and agricultural engineering (Edwards & Briers, 2000; Witjes et al., 2006). We also know that it is taught in non-engineering disciplines (e.g. management (Jackson, 2000), psychology, science and in k-12). Besides that, industry is also interested in knowing how to assess systems thinking for training and recruitment purposes. Research has shown that these academic and professional communities lack useful tools to evaluate students' and practitioners' ability to deal with complex problems or their level of systems thinking. (Davidz, 2006; M Hopper & Stave, 2008; Megan Hopper, 2007; Stave & Hopper, 2007). Contributing to an explanation of how people learn or develop systems thinking would help these communities to create more accurate tools to assess this skill and specifically to academic communities to create better curricula to move learners forward in their ability to address complex systems more effectively. Besides, engineering needs its own learning theories because the problems that engineers face are different than those from other disciplines.

CHAPTER 2. LITERATURE REVIEW[2]

2.1 Introduction

As described in the previous chapter, this study seeks to investigate the developmental path for the ability to address complex systems. In this chapter, you will find the foundational knowledge that frame this study. The first section describes concepts in regards to systems that would be useful to understand the nature of the systems that participants in this study were asked to address. The second section presents literature on systems thinking. The third section shows conceptual alternatives that explains the development of systems thinking and its assessment. Finally, you will find a brief description of my viewpoint on learning, and an explanation of *"Variation Theory"* (Marton, 2014), the learning theory that I used as conceptual framework in this study. The chapter ends with my research question expressed using the language of variation theory.

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[2] A preliminary version of the first three chapters of this dissertation were published in Mendoza-Garcia J., Cardella M., Oakes W. Various ways of experiencing dealing with complex problems. Frontiers in Education. Madrid, España. © 2014 IEEE. The paper is available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7044347&tag=1

2.2 Systems, complex systems, and complex socio-technical systems

Since it is my goal to reach different audiences, before presenting what is known about systems thinking, and its learning and assessment, it is necessary to establish a common language on what is a system and a complex system. The literature in this regard is enormous, and it is not my purpose to have a complete grasp of it, but to set a baseline knowledge that can inform you as a reader, about concepts and ideas you will be finding recurrently in this document. The key idea is that, after this chapter, whenever you find me discussing complex systems, I mean “complex socio-technical systems”, which are the kind of systems, engineers will be involved in designing for the real world.

2.2.1 System

This section is presenting ideas from classic authors (Bertalanffy, 1956; Boulding, 1956), and from two textbooks I used when teaching my classes in systems thinking (Bertoglio & Johansen, 1982; Capra, 1996). A system is described as a set of components that work together to reach a goal. It has at least one input that the different components use to create at least one output. The output is the result of the interaction between the various components and cannot be explained by studying the parts in isolation, but within the context of a larger whole by describing the relationships among the parts. The elements of the system are diverse, and they could be machinery or living beings. Systems can also be understood as “closed” or “open.” They are closed when the system does not try to adapt or does not respond to changes in the environment that surround it, and it is open when it does.

2.2.2 A systems classification and complexity

Different authors from systems science, management, and technology have proposed systems classifications. Intending to create a threshold for your understanding of the different kind of systems that I recognized from the literature, I am presenting a classification in Table 2.1. This classification is based on Boulding (1956), who presents a view from the systems science; Ackoff & Gharajedaghi (1996, 2003), who proposed a classification from the management science perspective; and Grabowski & Strzalka (2008) that is made with a technology perspective. You will also find in Table 2.1 that I am using a funnel approach from left to right that starts with two kinds of systems: "closed" and "open" systems (Boulding, 1956).

General Systems Theory proposed that the closed systems are those that do the only input they accept from the environment is energy. Machines and mechanical systems are understood by general systems theorist as closed systems, because beyond only receiving energy from the environment, their inputs are defined once and for all. Therefore, its output is deterministic, which means that for a specific input, the system's output would be the same. There was a time in which the world was seeing as a machine, which was called the era of the mechanistic thinking, and the rules that defined that vision of the world were defined by the scientific method which laid the ground for empirism (to rely only empirical evidence), determinism (follow the cause-effect principles) and monism (inseparability of body and mind) (Skyttner, 2001).

In contrast, currently, the world is seeing as a system, and the vision of the world as a system follow in general the premises developed by the General Systems Theory. Still, the way to see the world as a system might vary among people. In this regard, we can use the systems classification to talk about how people might see systems. General Systems Theorist like Boulding (1956) made its classification of systems differentiating the closed systems as simple, and the opened systems as complex. However, with the increasing number of technological components in technological is classification, there are two types of closed systems: simple and complicated. The difference between them is expressed by Grabowski & Strzalka (2008), regarding the number of parts of the system. Simple systems are those with a small number of parts, and complicated ones have a huge number. Still these systems are deterministic which means that their "behavior and properties … are determined by their structure, causal laws and - if they are open systems – by other systems in the environment" (Ackoff & Gharajedaghi, 2003, p. 3)), and regarding decisions, neither the parts or the whole can make decisions beyond those that are already determined (Ackoff & Gharajedaghi, 1996, 2003). Something interesting is the relationship that these simple and complicated systems have with complex systems regarding their purpose. Simple systems have no purposes of their own, but they "normally serve the purpose(s) of one or more complex systems" (Ackoff & Gharajedaghi, 2003, p. 3).

Open systems, on the other hand, receive inputs from the environment and use that information to adapt to the changes in it. In Table 2.1, I am citing four kinds of systems that will be useful later when defining the data collection methods in Chapter 3: ecological, animate, social, and socio-technical. The first three are proposed by Ackoff (1996, 2003), and I am including the fourth one because of its relevance for engineering (Trist, 1981). All of them are complex, but their complexity varies in regards of "the number of variables, and the nature of their interactions that are required to explained the properties and behavior of that system" (Ackoff & Gharajedaghi, 2003, p. 15). Another way to see the complexity in systems is in regards of choice which is presented in Table 2.2.

Table 2.1 - Systems classification based on Boulding (1956), Ackoff (1996, 2003), and Grabowski & Strzalka (2008)

Type of system			**Description**
Closed	Deterministic	Simple	A small number of parts, and a goal. Usually have a function in a more complex system.
		Complicated	A Huge amount of parts. Can adjust to changes in the environment but the range of these changes is limited.
Open	Deterministic	Ecological	Parts can make choices but the whole cannot, the effects of the behavior are determined.
	Non - deterministic	Animate	Respond to changes in the environment by making decisions after considering information.
		Social	A human plays a role in an organization. This system is a set of roles tied together with channels of communication
		Complex Socio-technical	Similar to social but with a pervade use of technology for gathering information to support decision making, or for communication.

Here is an explanation of each system in the Table 2.1 explaining how choice is seen in these: [1] An ecological system's behavior is mostly deterministic, but still is complex because each part interacts with the environment and can make decisions, while the whole cannot (Ackoff & Gharajedaghi, 1996, 2003). Cited examples are a flock of ducks (Grabowski & Strzalka, 2008), an island, or natural phenomena like tornadoes (Capra, 1996). [2] An animated system is composed of several deterministic systems, some of those provide more sophisticated methods to gather information from the environment to aid its decision-making. In these systems the parts have functions but cannot make decisions by themselves, the whole is the one that makes decisions, following a centralized decision making model. The typical example is an animal or a human being. The parts, like the heart, are deterministic in their function. Likewise, the senses get more sophisticated than those for example in plants and send that input to the brain so the whole can make a decision. For example, if in a human being its temperature sensors sense that it is cold, then she might make the choice of putting a jumper on [3] In a social system the complexity increases because several animated systems compose it. They receive information, process it and make decisions individually, following a distributed decision making model, and also make decisions collectively (Ackoff & Gharajedaghi, 1996, 2003). In this dissertation, animated systems will be understood as "human beings". We, human beings, cooperate with other humans, and our relationships are determined by a not necessarily well-defined set of rules. These rules can be changed at any time at the discretion of the members of the system so the system can be adapted to the variations in the environment (Grabowski & Strzalka, 2008). [4] Finally, there is a classification called socio-technical systems (Trist, 1981), also called complex engineering systems (Magee & de Weck, 2004). These are those systems composed of a high number of humans using technologies to collect and process information the individuals or the system as a whole use for decision making. Accordingly, interaction in the system could be between one or more people, or between one or more individuals with a technological artifact or device, or between technological artifacts without involving people, but affecting the people. Magee & de Weck (2004) also proposed that two essential characteristics can be used to describe complex engineering systems, that I will keep calling in this study complex socio-technical systems: function and output.

Table 2.2 – Choice in systems based on Ackoff & Gharajedagh (1996, 2003)

	Choice		
Type of System	**Parts**	**Whole**	**Example**
Simple	No choice	No choice	A clock, a bee, a tree.
Complicated	No choice	Limited and predictable choice	
Ecological	Choice	No choice	A flock of flying ducks. People using products that affect the ozone layer. Here, the earth cannot decide not to decreased the ozone layer.
Animate	No choice	Choice	A person
Social	Choice	Choice	A company, a county, a city.
Complex Socio-technical	Choice	Choice	Similar examples involving the high use of technology.

According to their function, complex socio-technical systems could either transform things into objects (transformation systems), or provide transportation (distribution systems), or hold objects over time (storage systems), or allow for the exchange of objects (market systems), or drive objects to a desired state (control systems). On the other hand, regarding outputs, a socio-technical system can be described as a producer of Matter, Energy, Information or value (monetary). This classification was also useful for me when defining the tasks.

The open systems described previously are related as follows: An *ecological system* can contain one or more complex *socio-technical systems*, which are composed of human beings working together to achieve the goal of the organization (as in a *social system*), and at the same time, to reach their aims (as in an *animate system*). For doing their jobs, people in the system can use technological artifacts to gather information that allows them to make decisions for better coordination and communication among them (as in a simple and a *complicated system*). In the end, the output of each system is created due to the interaction between the parts (as in a *complex socio-technical system*). For example, the land where the US is, was divided into states. The land is an ecological system. Each state contains counties. Counties have cities and cities have companies producing different outputs and performing different functions. It is relevant to mention that across all these levels there are people seeking to reach their goals.

2.3 Systems Thinking

As we all might know, some engineers do better than others when they intervene in an already complex system with a new engineering artifact. They could intervene by developing a new alternative that allows you to declare your taxes electronically, or developing a new experience for owners of a specific phone brand, or improving a process in an organization, or creating a new system that could help a city or a county to respond effectively after a catastrophic event. A possible answer is that they are better at the ability to address complex socio-technical engineering systems, which in the literature is called “systems thinking”.

The literature that explains systems thinking is huge, as it was the literature on systems. For example, the International Encyclopedia of Systems and Cybernetics (François, 2004), cited by Cabrera, Colosi and Lobdell (2008) compiled nearly 3800 definitions from approximately 1200 sources. These authors also cited a visual map of systems thinking (Studies, Schwarz, & Durant, 2001), and a four-volume set of the influential writings by systems thinkers (Midgley, 2003). However, most of this literature is not empirically grounded. I include in this section some of these definitions in Table 2.3.

Table 2.3 – Different definitions of systems thinking

Reference	Definition
Peter Senge (1990)	The highest level discipline in a learning organization that integrates and connects the other four levels he proposes for it (personal mastery, mental models, building shared vision and team learning)
Barry Richmond (Richmond, 1993)	Ability to operate in a subset of critical thinking skills simultaneously: Dynamic thinking: An "ability to see and deduce behavior patterns rather than focusing on, and seeking to predict, events. It's thinking phenomena as resulting from ongoing circular processes"(1993, p. 122) Closed-loop thinking: An ability to "see the world as a set of ongoing, interdependent processes … between a group of factors and a phenomenon that these factors are causing … external forces are seen as precipitators instead of causes … [the self is viewed as] responsible for generating the behavior pattern exhibited by the system (1993, p. 124). Generic thinking: Look for analogies between the feedback loop relations of different systems (Adapted by the author based on the description provided by Richmond (1993, p. 125)). Structural thinking: "It is here where people have to think in terms of measure or dimensions" (1993, p. 125) Operational thinking: "Think in terms of how things really work – not how they theoretically work" … "'[it] grounds students in reality … rather than dealing with abstractions" (1993, p. 127) Continuum thinking: An "ability to see connections and interdependencies rather than sharp boundaries … nourish by simulation … as opposed to discrete, modeling approach" (1993, p. 130). Scientific thinking: "it is not absolute numerical measurement … it has more to do with quantification than measurement … it is related to being able to quantified … It also means … being rigorous about testing hypothesis … modifying one thing at a time and holding all else constant" (1993, p. 131).
J. Sterman (1994)	The ability "to see the world as a complex system, in which we understand that 'you can't just do one thing,' that 'everything is connected to everything else.' "
Lawrence Henderson (Capra, 1996)	"The understanding of a phenomenon within the context of a larger whole."
Fritjof Capra (1996)	An ability to put interrelated things into a context, to establish the nature of their relationships.
Moti Frank and Waks (2001; Frank, 2002)	Engineering systems thinking: "Multifunctional" definition: ability to understand systems' aspects, its implications, its interrelationships and its interconnections. All of these to perform a function without constraints. The author provides also subcategories for systems' aspects, implications, interrelationships, interconnections, functions, and constraints.
Enrique Herrscher (Herrscher, 2003)	Is a mental ability that enables people to see various 'things' as systems.
Jamshid Gharajedaghi, cited by (Davidz, 2006)	"It puts the system in the context of the larger environment of which it is a part and studies the role it plays in the larger whole."
Heidi Davidz (Davidz, 2006)**	"Systems thinking is utilizing modal elements to consider the componential, relational, contextual, and dynamic elements of the system of interest."

Reference	Definition
	Componential: those types of things considered as behavior, objective, performance, data and management. Also includes a balance between social issues like politics, economics, organizations and technical components. Relational: Addresses interconnections, interactions, interdependences within the system of interest and with other systems. Contextual: The system belongs to other different systems. The system is embedded in other systems. Dynamic: Consideration of feedback, uncertainty, risk. Every system is impacted by the past and must anticipate future perturbations. Modal: related with "how" the systems thinker makes sense of the system and attempt to understand its behavior. He/she can use tools (simulations, frameworks, visual representations), different types of thinking (holistic, analytical, deductive, logical, visual, critical) or the requirements definition and validation.
Cabrera, Colosi, & Lobdell (2008)	Developed a conceptual model with four component rules or patterns: Distinctions, Systems, Relationships, and perspectives (DSRP). In this work, systems thinking is defined from different perspectives: "systems thinking is simply a way of reframing one's thinking in a domain, accomplished by a reconstruction of systems thinking based on the elements of DSRP allowing for a universal approach to manipulation of concepts relevant to all thinking in both professional practice and intellectual disciplines" … "systems thinking is not content specific" … "systems thinking can be readily learned and can be formally, explicitly and even algorithmically applied". (2008, p. 307).
Systems Engineering Body of Knowledge (BKCASE, 2012)	"Integrating paradigm for systems science and systems approaches to practice ... [and] … is concerned with understanding or intervening in problem situations, based on the principles and concepts of the systems paradigm. It considers the similarities between systems from different domains in terms of a set of common systems concepts, principles, and patterns".

Beyond defining systems thinking, it is also relevant to present its principles and values that make it unique, so you get an understanding of the way in which the literature depicts how a systems thinker could conceive the world around her. Since using contrasting cases facilitates the transfer of knowledge (Derry, Wilsman, & Hackbarth, 2007), I will cite Capra´s (1996) comparative between the principles and values of self-assertive ways of thinking, and the integrative ones (See in Table 2.4 the principles, and in Table 2.5 the values).

Table 2.4 - Principles of self-assertive thinking vs. integrative thinking based on Capra (1996)

Principles of two ways of thinking	
Self-Assertive	**Integrative**
Rational	Intuitive
Analysis	Synthesis
Reductionist (Focus on the parts)	Holistic (Focus on the wholes) – “the total system always represents more than the sum of its parts” (Skyttner, 2001, p. 66)
Linear (Cause-effect relations)	Non-linear (Circular cause-effect relations)
Focus on inputs and predicting outcomes	Focus on understanding the outcomes
Short-term	Long-term
Aggregation	“the whole cannot be explained by the sum of its parts”

As self-assertive, he mentioned rational thinking (follows the scientific method for decision making), analytical thinking (that focuses on static and structural properties) (Skyttner, 2001), reductionist thinking (divide in parts, and study the parts to understand the behavior of the whole (Skyttner, 2001)), linear thinking (“that assumes that for a given transformation process, the output variables are proportional to the input variables” (Bratianu, 2007, p. 154), which implies that if you know the input variables, and the process constants, you can determine what the output will be, which makes the system deterministic). On the contrary, the integrative thinking proposed were intuitive thinking, as a response to rational thinking, synthetic thinking, as opposed to analytical thinking, holistic thinking, as opposed to reductionist thinking, and non-linear thinking, as opposed to linear thinking. The values for the self-assertive ways of thinking are “expansion”, “competition”, “quantity” and “domination”, while the values for the integrative ones are “conservation”, “cooperation”, “quality” and “partnership” (Capra, 1996, p. 10).

Table 2.5 – Values of self-assertive thinking vs. Integrative thinking based on Capra 1996.

Values of two ways of thinking	
Self-Assertive	**Integrative**
Expansion	Conservation
Competition	Cooperation
Quantity	Quality
Domination	Partnership
Mind vs. Body	Whole person
External inputs	Self-regulation
Individual - Others are responsible, usually an individual who did one of the previous step (cause-effect). (Herrscher, 2003)	Collective: The system is responsible (Herrscher, 2003)
Extrinsic only (Herrscher, 2003)	Extrinsic and intrinsic (Herrscher, 2003)

2.4 Conceptual proposals for assessing systems thinking

Developing an adequate assessment of the learning of a concept or ability requires knowledge of how people develop that concept or skill (Pellegrino, 2002). It needs to go beyond describing the characteristics of a person performing well to describing a developmental path for this ability. In the systems engineering literature you can find characteristics of a good systems thinker, or in Frank's terms, a "High Capacity for Engineering Systems Thinking" (2006). This author presents clues on how an assessment tool could be designed using psychological testing to assess a person's interest in systems engineering positions to identify those with the potential to become successful systems engineers. He also used this tool to assess student's development of the capacity after a capstone project(S Koral Kordova & Frank, 2015; Sigal Koral Kordova et al., 2015). The weakness of this tool is that it relies on a survey in which participants are asked about their way of thinking, but it might be easy for a participant to score high, even if they don't have a high level of ECST. In the test, participants are asked about his agreement with statement A or B (S Koral Kordova & Frank, 2015, p. 2; Sigal Koral Kordova et al., 2015, p. 2):

> A - When I propose a solution to improve an existing situation in the project, I am aware of non-engineering considerations, such as business and economic considerations.
>
> B- When I propose a solution to improve an existing situation in the project, I focus only on operational and engineering considerations.

According to them, the engineer who has a capacity for engineering systems thinking is expected to choose sentence A in this example. The following example has B as the right answer: (Frank & Elata, 2004, p. 5):

> A - When I propose a solution to improve an existing situation in the project, I focus only on operational and engineering considerations.
>
> B - When I propose a solution to improve an existing situation in the project, I am aware of non-engineering considerations, such as business and economic considerations.

The way in which these two questions are stated makes me believe that anyone who wants to score high, and has the basis of what a systems thinker is supposed to be, would find a way to score high in the test. Considering this possibility is crucial in survey and assessment design (Creswell, 2012). Beyond being a test that can be deciphered by the taker, that approach would give me, as a result, a score, but not a path of learning.

Another assessment approach was focused on finding out if their participants, students from the MIT school of management, understand basic systems dynamics concepts (L. Sweeney & Sterman, 2001). Although researchers in this study found that these learners performed “poor” (2001, p. 251), they did not explain what would be the next step in the learner understanding to walk toward getting a similar knowledge on the task that the researchers had.

A developmental learning path was proposed by Hopper and Stave (2008). They proposed a unidimensional-hierarchical-learning path that followed the learning framework proposed by Bloom's revised taxonomy (Anderson et al., 2001). The authors presented their proposal at a systems dynamics conference, and the feedback they reported was that the linear model might not reflect the learning of systems thinking. Additionally, in that feedback they were told that some high level dimensions such as "creating simulation models", which for Hopper and Stave implied a high level of systems thinking, were not accurate because, for these participants who gave them feedback, not knowing how to create simulations, did not imply a low level of systems thinking. This feedback is useful for me because I know in advance that a linear model to explain the development of the ability to address complex socio-technical systems is not acceptable. The seven levels of Hopper and Stave's taxonomy, which are described developmentally from the top to the button, can be found in Table 2.6.

Table 2.6 - Hopper & Stave's developmental model for systems thinking. The level on the top is the least advanced, and the level on the button is the most advanced.

Level	Description
1	Recognizing interconnections
2	Identifying feedback
3	Understanding dynamic behavior
4	Differentiating types of variables and flows
5	Using conceptual models
6	Creating simulation models
7	Testing policies

Professional societies such as the International Council for Systems Engineering - INCOSE have developed their own assessment of the ability. Two components have this certification process, first, an exam, and second, professional experience. The written exam tests the knowledge the learner can recall from the System Engineering Handbook

(Walden, Roedler, Forsberg, Hamelin, & Shortell, 2015), and the evidence of professional experience, which is studied by experts who use a rubric to judge if that experience is good enough to reach a certification level. However, this rubric is not of public access and the process of how it was developed, if it was based on empirical findings or in conceptual models is not public either. Additionally, INCOSE's rubric would be difficult to be used in for example undergrad academic settings because it presupposes that the learner already has a certain level and knowledge of systems thinking. INCOSE also has two different initiatives related to this study. First, they are promoting systems engineering knowledge for all engineers, and second, they are developing a competency framework. In the first initiative, there have been two different workshops (2015, 2016) in which the first draft of learning outcomes regarding systems engineering knowledge for first year engineering and capstone projects were stated. The next steps should be taken in the direction of defining small instructional interventions that can be used for professors from different engineering disciplines. This study is a first step in developing ways to understand where a student is in her learning process, to move her forward.

On regards of INCOSE's competence framework (INCOSE - UK, 2010), they defined three main competences: [1] Systems Thinking, [2] Holistic life cycle view, and [3] Systems Engineering Management, Each with three different levels awareness, supervised practitioner, practitioner, and expert. Still, educational questions regarding how a learner might reach a level of awareness or even how they might reach higher levels remain opened.

Finally, the Systems Engineering Research Center at Stevens Institute of Technology, is currently working on a project in which they are understanding why a systems engineer is effective in regards to value created by "performing systems engineering activities in the positions assigned by the organization" that is called "The Helix Project" (Pyster, Devanandhan, Hutchison, Jauregui, & Clifford, 2015). The model is a result of the analysis of interviews conducted with junior, mid-level and senior systems engineers. As a result, the authors defined six proficiency areas: [1] math/science/general engineering, [2] System's domain & operational context, [3] systems engineering discipline, [4] systems engineering mindset, [5] interpersonal skills, [6] and technical leadership. I will not explain each of them here, but these areas are concern about knowledge, skills, and behaviors. Additionally, the authors determined that there were forces that impact the proficiency of systems engineers. These forces are experiences, mentoring and education and training. Finally, the authors reported that personal characteristics and organizational characteristics are also key elements to determine the effectiveness of the systems engineers. You can find a graphical representation of this model in Figure 2.1.

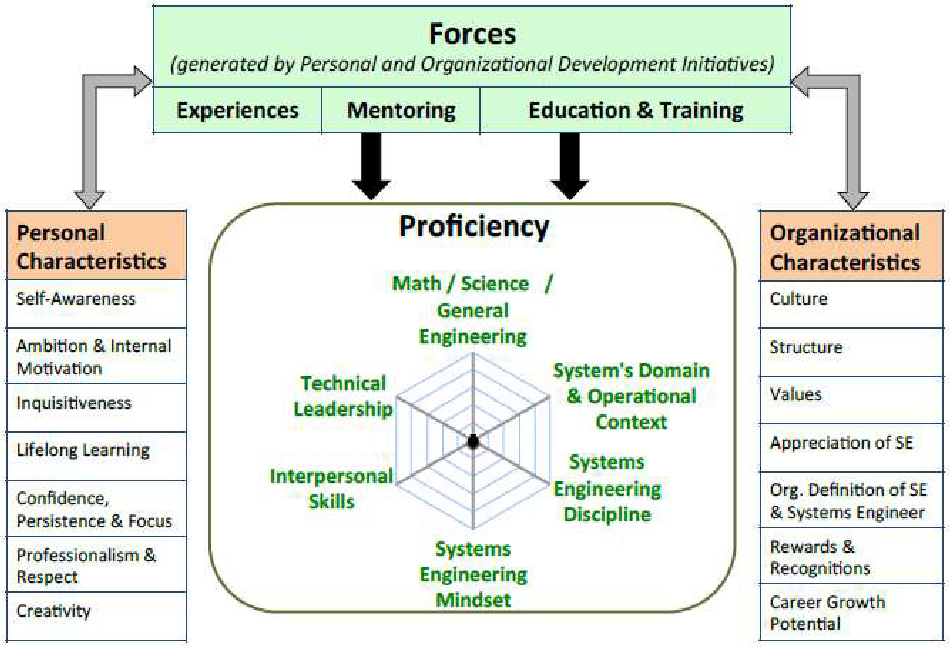


Figure 2.1- Model of proficiency of systems engineers developed by the Helix Project. Image borrowed from Helix project document (p. 48)

In addition, this project also analyzed the career path of chief systems engineers trying to establish the kind of experiences that allowed them to get that kind of positions within the organization. My study will be complementing this study addressing by explaining what might make some more effective than others when addressing complex socio-technical systems. In addition, The Helix project is focused only on studying systems engineers, while in my study, I included participants from different engineering disciplines, and additionally, I included also undergraduate students from first to senior year.

As you can see, these theories of the development of the ability to address complex socio-technical systems are mostly proposed based on conceptual models instead of being grounded on empirical findings. Additionally, an assessment like the one proposed by INCOSE is expensive, it is not of public access, or accessible to academic contexts in non-systems engineering disciplines, and was not design to take into account professionals from other disciplines. In addition, it was not designed to consider undergraduate students, or even graduate students. A similar situation happens with the Helix project. My study is contributing to close in part this gap since my findings are grounded in empirical data collected from participants with different levels of expertise in addressing complex socio-technical systems, and the data was collected from undergraduate and graduate students, engineering faculty, and industry professionals. I also used “variation theory” (Marton, 2014) as a conceptual framework to be sure that the results were coherent with a way of learning already formulated by educational scientists. In the following sections, you will find the conceptual framework that defines my standpoint regarding learning.

2.5 Learning

In this study, my understanding of learning will be referenced within the framework provided by the constructivist theories in which the subject, is composed of mind, body, emotions, and is immersed in a social world, instead of an empty passive being who is filled with knowledge (Mahoney & Granvold, 2005). These theories explain that learning happens because of the experiences of the subject in the world. Doing, thinking, feeling and interaction with others are the kind of experiences that promotes learning (Dall’Alba, 2009; Heidegger, 1962; Jarvis, 2006). By experiencing the world, by interacting with it, the learner and the world are transformed. This idea of a learner who gets transformed and who transforms the world by experiencing it leads to the conception of learning as a result of the previous experiences of the learner, or a developmental process in which you build new knowledge based on “what you already know and believe” (Bransford, Brown, & Cocking, 2000, p. 10).

Learning experiences can happen within a classroom (formal setting or environment), or outside the classroom (informal learning) (National Research Council, 2012; Tolbert & Cardella, 2013). Marton (2014) calls the former learning as an aim, implying the need of effort from others to help to learn, and the latter, learning as a “byproduct of doing things for reasons other than learning to do them” (Marton, 2014, p. 31).

The ideas of experiential learning within formal and informal environments were taken into account when defining the participants who were invited to the study. As you will see later, my study included undergraduate and graduate engineering students, engineering faculty, and engineering industry practitioners with one to more than 20 years of experience. Graduate students, faculty, and professionals were born, educated and worked in different countries. The undergraduate students also had diverse experiences. Some have worked, some have been leaders in student’s organizations, and some others have none of these experiences at all.

2.6 Possible explanations of the learning of systems thinking

Davidz (2006) found that experiential learning (a set composed of “work on diverse things, systems jobs/experiences, family, early life experiences, hobbies”) is a key enabler of systems thinking. 67% of her participants (139/202) responded it was, while systems courses/degree were not frequently identified as an enabler (only 6%, or 13/202, responded it was). Based on this finding, it is plausible to think that, by experiencing practices that are like those of the real world, students might be developing systems thinking.

Besides experiential learning, formal learning environments in which the principles of complex systems are taught might be necessary to foster the ability to conceptualize, understand and deal with the problems that arise from them. At first, this learning environment should promote conceptual change (Chi, 2000; Vosniadou, 2008) since this change is necessary for systems thinking development (J Doyle, Radzicki, & Trees, 2008; JK Doyle, 1998; Senge, 1990; Sterman, 1994). However, this conceptual change or change of mental models is not easy for learners because they are counterintuitive or difficult (Schwartz, Varma, & Martin, 2008). For example, Chi (2005) explains that students base their understanding of the world in what they can perceive and see. Because of that, Chi explains, their misconceptions are robust. In the same way, Sweeney & Sterman (2001) cited 11 studies from which it can be inferred that systems thinking abilities are not innate but should be learned. Likewise Sweeney & Sterman's study (2001) found that their subjects, students in undergraduate, masters and Ph.D. programs, in general, score low on their systems thinking inventory test.

Some educational strategies that could be developing this ability are those student-centered ones in which students are involved in a team that addresses real-world problems. Some of these initiatives from engineering schools are service learning in engineering (Coyle, Jamieson, & Oakes, 2005; Lima & Oakes, 2006), with programs like Engineering Projects In Community Service - EPICS, global engineering programs (e.g.

the one at Purdue University in which students work in a problem to support a community outside of the US), and PROSOFI from Pontificia Universidad Javeriana in Colombia (Mendez & Perez-Muzuzu, 2013), that has students from different disciplines working together for a semester in projects for a socially vulnerable community in Bogotá. Besides bringing real-world to the classroom, there are initiatives that aim to reproduce real world situations and environments to foster students' understanding of it; for example, the CDIO (Conceptualize, Design, Implement and Operate) initiative (Crawley, Malmqvist, Lucas, & Brodeur, 2011), and approaches for teaching human-centered design which enable students to deal with complex problems or "wicked" problems (Cardella, Zoltowski, & Oakes, 2012). One example is "Alien-Centered Design", in which students work on a problem for users completely different from themselves, and in the process develop empathy, while students also engage in reflection and iteration ((Jordan, Lande, Cardella, & Ali, 2013; Mendoza-Garcia & Cardella, 2014).

The previous paragraphs support the idea that systems thinking is a subject that needs to be taught to promote the conceptual change needed to understand the inherent complexity of real-world problems. The results from this study might be contributing with explanations on why these learning experiences are good for students' development of this ability, and could help educators to focus their teaching on increasing the effects of the learning experience.

2.7 Variation theory of Learning

This study is grounded in "variation theory", an empirical learning theory developed by Dr. Ference Marton as the result of his phenomenograhic studies that tackle the question of why there are people who are better than others at the learning of something (Pang, 2003). Most of this section is extracted from his latest book "Necessary conditions of learning", which I have read and re-read several times to be able to explain and appropriate the theory. Marton proposes that learning not only requires being able to identify the similarities between two problems from one context to another (transfer of learning (Bransford et al., 2000)), but also to be able to discern the differences (Marton, 2006). He proposes that learning is about a higher awareness of the "object of learning (that which is to be learned)" (2014, p. 14). According to him, the learner always goes from "undivided wholes [of the object of learning] to more and more differentiated and integrated wholes [of it]" (2014, p. 60). His model proposes that "for every object of learning, and for every learner, there are critical aspects and critical features, which the learners have to become able to discern" (2014, p. 39), and that by discerning these "critical aspects ... and *some* critical features simultaneously … [the learner] … enhance the likelihood of being able to discern the same or *other* critical features of novel tasks" (2014, p. 26), or in other words, the learner becomes able to transfer. Marton explains that an aspect, "is the experience of difference", and the features "are those things that differ." Now I am going to present you Marton's example that helped me to get a better grasp of what aspects and features are. An object can be described by its color, or by its shape. The experience of color happens when you can recognize that there is color. That experience happens by contrast. For example, if everything in the world was green, you will not be able to discern that there is color. However, if in that imaginary world, you introduce something blue, then you notice, by contrast, that this new object has something different than the others, which means that you are experiencing color, an aspect of objects. Green and blue, are features you needed (in that imaginary world) to be able to realize that there was color. Since color is an aspect we, as educators, might want the learners to learn to enable them to describe objects in a more powerful way, the aspect becomes a "critical aspect", and blue and green are "critical features."

As proposed above by Marton (2014), a critical aspect is differentiated because there was variation in *some* critical aspects the learner was able to focus simultaneously. Accordingly, because of this variation, a critical aspect is also known as a critical dimension of variation of just a "Dimension of Variation", and the features are also called "values within that dimension".

Learning, in Marton's terminology, can happen in two ways. In one, you learn when you can differentiate a new critical aspect of the object of learning, or in other words, you can open a new dimension of variation. This means that you become aware of two or more different features within that dimension, and it happens because you can contrast them. Learning also happens when you learn a new value within that dimension. According to Marton, the most difficult learning is to open a new dimension of variation.

The next question you may have is "how can I help a learner to open a dimension of variation?" Marton says that a learner has to experience difference against a background of sameness to be able to open a new dimension of variation. For example, if we apply this to the teaching of design, we can ask our learners to work on the same design task several times, including just one new dimension at a time (obviously, as instructors we need to know in advance what these dimensions of variation are), otherwise, it will be impossible for the learner to know what was the aspect that varied. You will find more on these suggestions in the final chapters of this document once I present the results from my study.

Finally, I will introduce you to the "path of learning" proposed by Marton, which I used after finding the dimensions of variation in my study to describe the hierarchical relationship between them (See the results section). There are four stages in his model: repetition, contrast, generalization, and fusion.

[1] Repetition means that the learner hasn't been able to open dimensions of variation, or in other words, the learner hasn't been able to make any distinctions. The learner will work on the task without being able to grasp any of the critical aspects of it.

[2] Contrast, in this case, means that the learner can open a dimension of variation, and focus on it while addressing the task. For our design task example, a possible critical aspect is an iteration. Opening that dimension of variation means that you may ask the learner to do the task without iteration, and later to do it with iteration. Students will learn by experiencing the difference, that iteration is critical to have a good design.

[3] Generalization, the next step in the path of learning, means that you learn more values within that dimension. For example, iterate only at the end, vs. iterate in all the different phases of the design process. The learner might be able to experience different results and might get attracted to the idea of iterating as much as she can.

[4] The last level is fusion. Let's suppose you taught your students about two critical dimensions of variation in the design process: iteration, and effort in problem definition.

In generalization, the previous level, learners are not tackling all the aspects simultaneously, but one at a time. In the fusion stage, the learner experiences all the aspects simultaneously, so she experiences simultaneous variation in all relevant aspects of the object of learning. In our design task example, the learner is supposed to focus on the effort in problem definition, and at the same time, consider that iterating in problem definition is part of the effort she needs to make to have at the end a better design.

Different moments in which a learner could be on the path of learning, which is also known as ways of seeing the object of learning, or meanings of that object of learning, are called categories of description. These can be expressed in terms of the dimensions of variation that are opened up by the learner, and values within that dimension that the learner should be able to recognize.

2.8 The research question stated in terms of variation theory

Since it was my goal to find a path of learning for the ability to address complex systems, and I found that variation theory was an acceptable way to frame my research, it was logical to re-state my research question in terms of variation theory to make it more accurate:

> What are the various ways in which engineering undergraduate, graduate students, faculty, and practitioners experience addressing Complex Socio-Technical Systems?

2.9 Conclusion

In this chapter, I have reviewed literature that builds the concept of complex socio-technical systems to provide context for the kind of problems that I am interested in our engineering students getting better at addressing. I also presented different concepts that have fed my understanding of systems thinking, and conceptual proposals that have been developed to assess systems thinking and that can be used to explain how it is developed. I also present the theories that defined my perspective on learning and some possible explanations of the learning of systems thinking.

Finally, I presented variation theory of learning and restated my research question based on variation theory of learning, and the kind of systems I am interested engineering students get better at addressing.

CHAPTER 3. THEORETICAL FRAMEWORK AND RESEARCH DESIGN

Based on findings using the phenomenographic research approach, Marton developed “variation theory.” Since I am using variation theory as a theoretical framework, it was logic to use phenomenography, and especially Marton’s “new” phenomenography (Pang, 2003). However, this was not logic for me at the beginning, especially because of my lack of knowledge on both, variation theory and phenomenography. In this chapter, you will find first an explanation of my theoretical framework, phenomenography, and how I instantiated the framework in my research design addressing possible quality concerns that you may have as a reader (validity, transferability, generabizability, and reliablity). I also described how I gathered information to decide if it was better for me to use the Australian approach or the Swedish one. Finally, you will find my thought process regarding data analysis. There were 16 iterations, and they are described to show the transformation between early stages to the final one.

3.1 Theoretical Framework

3.1.1 What is phenomenography?

When I started this study, I did not know what phenomenography was, and how the three different approaches to phenomenography were similar and how they were different. I will present here a general definition and then a brief comparison of the three approaches.

Phenomenography is a research approach that is used to describe the different ways in which a learner might experience an object of learning. It was developed in the 70's in a research group in education in Sweden when its researchers (Marton, Dahlgren, Säjö and Svensson) were trying to investigate these two questions: (1) 'What does it mean, that some people are better at learning than others?'; and (2) 'Why are some people better at learning than others?' (Pang, 2003). Aligned with these questions is the understanding of a dualistic ontology of the world that is neither objective (out of the individual), nor subjective (as a result of the interpretation of the individual) but both. I will try to explain this dualism using ideas from Martin Heidegger (1962). He stated that we were thrown into the world, not alone, but with others. In that world, we are usually in a "peaceful" state of mind, until there is a disturbance, which usually is a problem that takes us out of that state. In that case, we "see" the problem, and we "act", according with what we "see" (Marton, 2014), using all the cognitive tools we have at hand (whatever we have deeply learned), and our body to work toward finding a way to come back to the "peaceful" state of mind. However, since not everyone has the same previous experiences, what people "see" as characteristics of a problem, might be different from one person to another. Likewise, what people "do" to tackle the problem is in correspondence with what they "see" (Marton, 2014). This idea might be related with the findings from the study comparing the practice of experts and novices when engaged in addressing the same design task. In this case, even though it was the same problem, novices might be seeing a straight forward problem, while experts might have been seeing a complex one because they might have known about issues to take into account that was not known by novices. (Atman, Adams, & Cardella, 2007).

In the design example, I just mentioned two ways in which the design problem from that study might be seen and addressed are novice and expert. However, there could also be several ways in the middle. Finding out all these possible ways of seeing the problem, and how they are hierarchically related from low to high level of awareness is the goal of phenomenography. Therefore, for phenomenographers, the study would be incomplete if they just focus on one individual's experience or way of seeing the phenomenon, or in just describing the phenomenon.

3.1.2 The phenomenon under investigation

As you read in the first section of this document, I was interested in developing a descriptive developmental path for the ability to address complex socio-technical systems. Accordingly, following the phenomenographic framework,I was interested in identifying the different ways in which a problem in a complex system might be seen and approached. These ways are internally related following a hierarchical relationship, and it is that relationship between the ways of seeing the problem what makes phenomenography different from other research approaches suchs as content analysis. Phenomenography follows a non-dualistic philosophy, which means that the person and the phenomenon are not considered independently, but instead, by studying the experience they both are considered together. Phenomenography is a qualitative research framework that uses a second order perspective, which means that beyond the experience, there is an interpretation of it that is performed by the interviewee during the data collection phase, or by the researcher in the data analysis phase. Additionally, it is focused on identifying and understanding the variation among these experiences. The Figure 3.1, shows the points of departure between phenomenography and other research approaches.

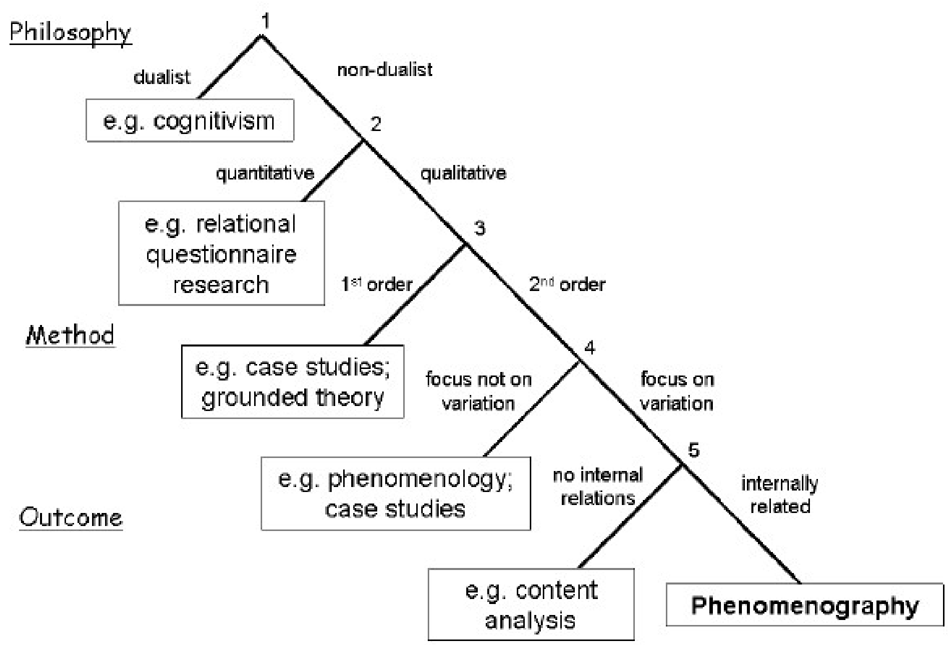


Figure 3.1- Points of departure between phenomenography and other research approaches. Trigwell (2000) cited by Mann, Dall'Alba & Radcliffe (2007

3.1.3 The second order approach in phenomenography and my stand on bracketing

Phenomenography is described as a second order approach (Mann, Dall'Alba, & Radcliffe, 2007; Marton, 2014), which means that it goes beyond describing what is in the data, to describe the meaning of what it is in the data. These meanings emerge after the researcher experiences the variation in the data, which means that you cannot give meaning to the data if you study the answers from just one participant in isolation. I will add in this respect the following quote from Marton (2014, p. 87):

> The … [researcher]… looks at the drawings against the background of other drawings produced by other children, or by the same children at another point in time and makes sense of them regarding aspects and features discerned and focused on

In regards of bracketing , Marton (1994), said that the researcher needed to bracket pre-conceived ideas because she was "supposed to focused on similarities and differences between the ways the phenomenon appears to the participants" (1994, p. 4428). Ashworth and Lucas (2000) also stated that during the interview, "bracketing yourself" was key for creating a sympathetic interview with the participant.

On the contrary, in this regard, Cope (2000, p. 83) stated that:

> Analysis does not involve imposing preconceived categories on the data, rather, analysing the meaning underlying the data from the perspective of scholarly knowledge. In the empirical study the categories of description were constituted as a relation between the researcher and the data. This process acknowledges the role of the researcher's scholarly knowledge in the data analysis process. The data is viewed from the researcher's perspective and researched scholarly background. The categories of description represent the researcher's experience of variation in the data

In fact, Marton's position changed. First, after searching in a digital version of Marton's 2014 book, I had a physical and a digital version, for the root word "brack", no matches were found, and second, in his 2014 book, he presents a case in which the researcher does not bracket herself from the phenomenon (2014, p. 93):

> in order to formulate a question, a problem, you must have some idea of what kind of differences you (as the author of the question) are interested in. Before Neuman [the woman performing the study] even started her study, she suspected

> that part-whole relationships between numbers (i.e. how numbers are divided up) are fundamentally important for how arithmetic problems are mastered. Accordingly the first question she asked, …

Here we see that Newman did not bracket herself. On the contrary, her knowledge in arithmetic helped her to design the interview questions, ask probe questions, and develop the outcome space (see p.98). Additionally, some researchers doing phenomenographic studies have stated their difficulty bracketing themselves. Cummings (2015) mentioned that, although bracketing was a requirement for phenomenography, it was impossible for her as a "human being" to do it. Dringenberg (2015), stated that she had difficulty to bracket her "own perception of the experience of the participant in the aim of understanding their experience" (2015, p. 38).

In my case, I did not bracket myself from the study. I am a Systems Engineer with experience in industry as a software engineer for 7 years. I am faculty and have taught system thinking in the past. I have an authentic interest in developing systems thinking in engineering students and in spreading systems engineering knowledge across all engineering.

3.1.4 Approaches to Phenomenography

As stated at the beginning, there are different approaches for phenomenographic research. Marton, its creator, has developed two frameworks (Pang, 2003), and Bowden (2000) one that he called developmental phenomenography, which in this document will be also called the Australian approach. Åkerlind also mentioned that there are Australians who approach phenomenography differently (2016), and Nordic researches like Booth also approach their phenomenographic studies differently. All of the approaches have been extensively used in engineering education, although in the school of Engineering Education at Purdue University, the one used the most by Ph.D. students have been the Australian approach with an emphasis in the developmental or Bowden's one. In this study, I used a blended approach, using Marton's second for finding the dimensions of variation, and Bowden's for establishing the hierarchical relationship structure between the dimensions of variation.

Table 3.1 – Comparative of the two phenomenographic approaches used in this study.

	Developmental (Bowden - Australia)	**Martons' New (Sweden)**
Data Collection	Ask for past experience with X	Ask to experience same instance of X
Data	People talking of "different things"	People talking about the "same thing"
Unit of analysis	Whole transcript	Ways of dealing with the task
Researcher's job	seek common meanings in the "different things"	Looks for variation in meanings of the "same thing"
Data analysis	Sort transcripts in groups, from less powerful to most powerful	Search for dimensions of variation – pool of quotes
Bracketing?	Yes (supposed)	No

While in the following sections you will find a more detailed description of the three different approaches to phenomenography, in Table 3.1 you can find the distinguishing characteristics of the two approaches used in this study.

3.1.4.1 Marton's phenomenographies

Since I am using Marton's second approach to phenomenography first, for finding the dimensions of variation, I will start discussing this approach. Marton started his research in the 70's asking "(1) what does it mean, that some people are better at learning than others?; and (2) why are some people better at learning than others?" (Pang, 2003, p.

146). Studies seeking answers to these questions employed phenomenography in the 80's as a research approach (Pang, 2003). This research aimed at (Pang, 2003, p. 147):

> Describing qualitative different ways in which people make sense of various kind of phenomena in the world around them. The questions that phenomenography addressed were 'what are the different ways of experiencing the phenomenon' and 'how are these related to each other?

Phenomenography was also found to have pedagogical potential (Marton, 2014). In this regard, the research question changed from (Pang, 2003, p. 147):

> attempts to describe different ways of experiencing various phenomena to attempts to answer "what is a way of experiencing something" and "what is the actual difference between two ways of experiencing the same thing" [emphasis added]

The understanding of this new research question was crucial to my understanding of what I was looking for in the data, which I can explain as following (paraphrasing in part Marton's, 2014. Note 12. P.149). In the first approach to phenomenography, participants are asked about their way of experiencing 'X.' X has been in the past at the school of Engineering Education at Purdue "human-centered design" (Zoltowski, 2010), "problems involving multiple possible solutions" (Dringenberg, 2015), interdisciplinary learning (Ming-Chen Hsu, 2015), and several other instances. Although all these authors used the Australian approach (or developmental phenomenography), the way they collected the information is similar to the way in which Marton does in his first approach. It is also similar the fact that what they look for similar meanings of experiencing the phenomenon in the data in a set of different instances of it. It is an inductive process. On the contrary, in Marton's second phenomenography, what you look for is the variation in experiencing the same thing (the same instance of the phenomenon), which is called a "background of sameness" (Marton, 2014). For example, when I designed this study, I designed two interviews, which I piloted. One following Marton's first (or Australian), and another following the idea for new Marton's. The interview following the first tradition asked participants about their experiences with complex systems. The two people I interviewed using that approach talked about very dissimilar experiences, and although I was able to see the variation, it was really difficult for me to find the commonality. That was one of the reasons why I designed the second interview using Marton's newer method. In that interview, I tested five possible tasks that I either found in the literature or designed, to be interpreted as a problem in a complex systems and elicit systems thinking. By having the participants addressing the same task, or in other words the same instance of the phenomenon, I started to see variation in the skill addressing the same tasks, which encouraged me to keep going in the direction I finally went. I will describe these two tasks in the research design section later in the document.

3.1.4.2 Developmental phenomenography (Bowden's phenomenography)

Developmental phenomenography is one kind of Australian phenomenography. Bowden in 2000 made a step aside from Marton and developed his approach which he called "developmental phenomenography." Bowden argues that his kind of phenomenography is developmental because it cares in informing people and teachers about the place where they are to help them to make the decision of moving forward in knowledge (Bowden, 2000). In a personal communication with Åckerlind, a well-known Australian phenomenographer, she explained that developmental phenomenography “advocates a practical educational purpose, which limits the range of phenomena investigated and has associated implications for using the outcomes of phenomenographic research developmentally” (Åkerlind, 2016). That might be a difference in regards of first Marton’s phenomenography, but currently Marton, through variation theory, is also interested in studying educational phenomena, and the outcomes are also used developmentally, or in Marton’s term, in a hierarchical structure. However, the main difference between the two is the unit of analysis. While in Marton’s the Unit of analysis is a way of dealing with the task, in the developmental, the unit of analysis is the whole transcript. This means that what the researcher compare in the Marton’s approach are meanings that can be extracted from the quotes, while in the developmental, the researcher compares the level of awareness that a given participant has with the phenomenon under investigation, vs. another participant’s level of awareness of this phenomenon. The other fundamental difference is regarding data collection. The Australian approach followed the strategy of Marton’s first phenomenography, asking the participant about their past experience with the phenomenon, while Marton asks all of them to deal with the same instance of the phenomenon.

3.1.4.3 Data analysis in phenomenography

The key difference between Marton’s first, and second, vs. the developmental phenomenography is that the latter develops his categories of description directly from participant’s performance. That is why developmental phenomenography uses the whole transcript as a unit of analysis. Marton, on the other hand, has a different approach to the data. First, read the transcripts completely several times (same as Bowden’s). Second, identify quotes that could have in Marton's first, similar meanings; and in new Marton's dimensions of variation, or similar aspects that show variation. These similar meanings in the Marton's first, and dimensions of variation in new Marton's, can be seen in contrast with the whole transcript, but especially when compared with other transcripts. Then you collect these quotes in what Marton calls a "pool of meanings," taking out the participant. You organize the quotes as evidence of the category of description (Marton's first), or evidence of the dimensions of variation (new Marton's). In this respect, one or more quotes from different participants could be representative of a dimension of variation in a pool of quotes. From there you "discover" the dimensions of variation. The goal is to identify dimensions of learning that can be opened by the learner or are closed to her awareness and not yet learned or employed during the interview. Studying the different possible combinations of dimensions that are open and closed to the learner's awareness gives you the hierarchical relationship between the dimensions of variation, and consequently between the categories of description of the experience. For identifying the dimensions of variation, I used the pool of quotes strategy, which allowed me to see variation across a topic. When defining the hierarchy across the different dimensions, I used the whole transcript strategy. I started with the idea of not using whole transcripts at all, but I found out that this hierarchy between the dimension of variation required, at least for me, a bigger context, which in my view was only provided by the whole participant's experience of addressing the task.

Regarding the use of quotes, in my journal I wrote once against the use of the whole transcript (sometimes, as it is shown here, I write my reflections in the third person) (Reflection Journal, 04/2016):

> Studying this variation do not require you to go back to your participants. They were important because they helped you by giving you one or more possible meanings, or opened one or more dimension of variation for you during the interview. It does not mean that the participant is not able to talk about other more advance meanings, or able to open more dimensions of variation than those used during the interview. It just means that during the interview, the participant just focused on those meanings or dimensions of variation that were relevant to her at that moment. Maybe if you do the same interview in another place, or at a different time, the participant could have given you the same data or a different one. That is why for Marton, it is not about categorizing participants, but using the data they provide to discover the categories of description.

However, using a similar argument, I decided to compare the transcripts, not the people. Åckerlind, in her personal communication, also explained in this regard (Åkerlind, 2016):

> I would argue that the hierarchy constituted in a phenomenographic analysis is one of inclusiveness, not one of value judgments. That is, it is not that the researcher personally values one way of experiencing more than another, but that one way of experiencing demonstrates awareness of a greater number of critical aspects than another. The ways of experiencing that are positioned higher in the hierarchy share awareness of critical aspects of the phenomenon with the ways of experiencing that are lower in the hierarchy, but also include awareness of one or more additional critical aspects. This expanding awareness of an increasing number of critical aspects is what constitutes the hierarchy and marks the structural relationships between different categories. But it is based on empirical evidence of inclusiveness, not on the researchers' personal value judgments

In Figure 3.2 you can find a representation of the blended phenomenographic approached I followed for this study.

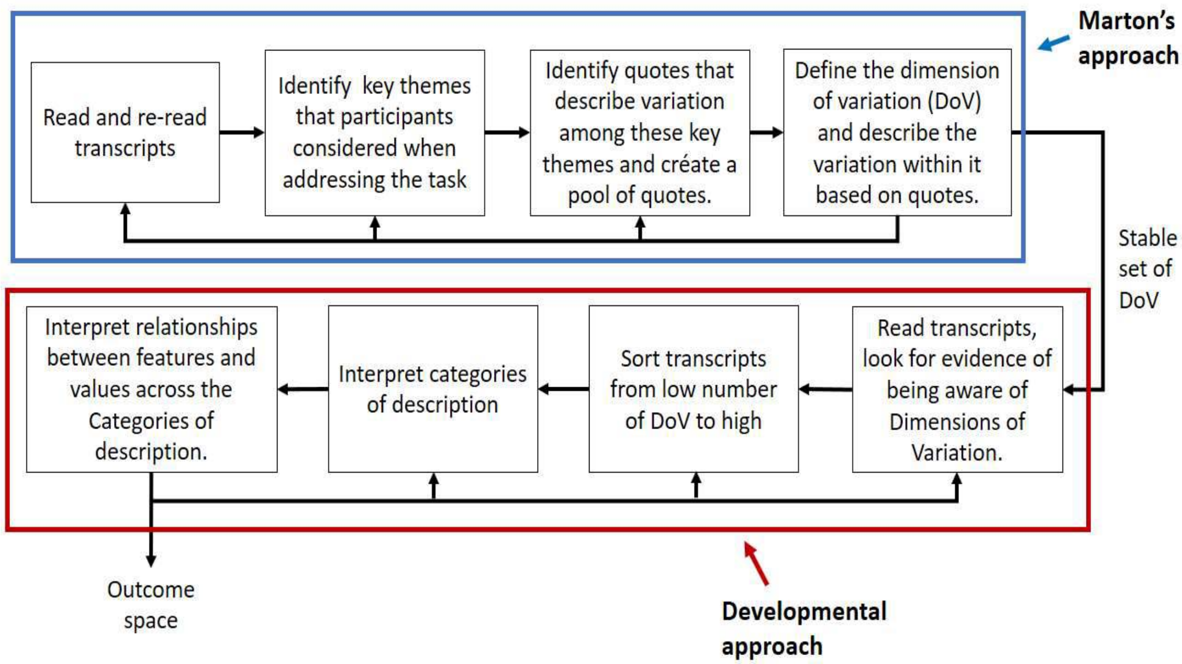


Figure 3.2 - Data analysis representation using the blended phenomenographic approach

3.1.4.4 The outcome space

The outcome space could be described differently depending on the kind of tradition that was followed when designing the research, especially the data collection. The key different is that in Bowden's approach the outcome space is not necessarily hierarchical, and the categories of description might not be logically connected (Bowden, 2000). This is because, since the participants are not sharing the same instance of the phenomenon but choosing what to talk about from their previous experiences, there is some probability that there are participants whose example of the experience does not fit with others' participants' experiences.

In Marton's approches, the outcome space is always hierarchical, implying that a higher level contains the previous one (Åkerlind, 2012; Marton & Booth, 1997; Marton, 2014). In the second approach, “new” Marton’s (Pang, 2003), Marton talks about levels of awareness of the object of learning. Since all the participants are sharing the same instance of the object of learning, it is logical then that a higher level of awareness about characteristics of, for example how to perform well a design task, contains a previous level of awareness of how to address it that are less powerful than the current one.

Even though the resulting outcome space could be different from one tradition (seeing the same thing) to the other (seeing different things), phenomenographers agree that, based on empirical evidence, a phenomenon can be seen in a limited number of qualitatively different ways (Marton & Pang (2008). Sandberg (1994, 2000) cited Alexanderson’s (1994) evidence of between 500 to 1000 research works and more than 50 doctoral theses). The number of studies keeps growing, and making phenomenography an acceptable research approach for answering questions regarding the learning of Engineering. At Purdue, in the Engineering Education Ph.D. program, several phenomenographic studies have been conducted so far. There are two studies running in 2016 (including mine), there were three studies in 2015 (Cummings, 2015; Dringenberg, 2015; Ming-Chien Hsu & Cardella, 2009), one study in 2014 (Salzman, 2014), one in 2010 (Bucks, 2010), and one in 2009 (Magana, 2009).

Conceptions (the qualitative different ways) should be understood collectively (and not individually) as a level of awareness of the whole, and its related to the sample of people that participated in the study (Åkerlind, 2012, p. 117). Still, the results are transferable to other contexts based on the variation of the sample considered in the study.

3.1.5 Why Phenomenography?

Beyond the most obvious reason that is the fact that variation theory, the framework I am using for my dissertation emerge empirically from phenomenographic researches, there are other arguments. First, as I explained at the beginning of this chapter, the experience of the phenomenon can be seeing in the practice, and the practice reflects what you see from the problem, and at the same time talks about the level of skill. Since a developmental path for a skill is what I am seeking to discover, it is logic to use phenomenography because it is focused on studying the experience of the learner with the phenomenon. Second, researchers following any of the three traditions has used it to study skills (e.g. Sandberg (1994), Dall'Alba & Sandberg (2006), Marton (Marton & Booth, 1997; Marton, 2014)).

The following is an example also shows why phenomenography can fit to study skills. In the work from Davidz (2006), she cited one interview in which the learning of systems thinking could be understood using variation theory. The interview was held with a military serviceman who worked on a nuclear submarine. He said that it was crucial in his systems thinking development his training to get the ship qualifications. There, he was able to spend at least one hour in each sub-system (sometimes weeks) and that he was aware of the whole ship not only of the stuff that was under his responsibility. Here we see that there was a background of sameness while the learner was able to experience some variation, but it was that variation that allowed the learner to understand the submarine's global picture. This idea of different experiences with a background of sameness showed that phenomenography can be used to study the variation of experiences, within the same learner at different moments in time, or with different learners all of them having the same experiences.

Finally, it is relevant to mention that phenomenography has been used in computer science education (Berglund, 2005; Berglund et al., 2009; Boustedt, 2008; C Cope, 2002, 2003; Marton & Booth, 1997; Stamouli & Huggard, 2006), engineering education (Bucks, 2010; Cummings, 2015; Dringenberg, 2015; Ebenezer & Fraser, 2001; Ming-Chen Hsu, 2015; Zoltowski, Oakes, & Cardella, 2012; Zoltowski, 2010), in economy education (Marton & Pang, 2008; Marton & Pong, 2005), and in health sciences (Barnard, McCosker, & Gerber, 1999; Brammer, 2006; Sjostrom & Dahlgren, 2002), among other fields. Finally, these are some examples of the kind of research questions that have been answered through phenomenography. Computer science education have used this method to answer questions such as "what it means and what it takes to learn to program," "How novice programmers learn to program?," "How novice students understand the computer science concepts of object and class" (Berglund, 2005), "how computer sciences' students experience learning object-oriented programming" (Stamouli & Huggard, 2007) and learning about information systems (Chris Cope & Prosser, 2005). In Science education, it has been used for example to find students' conceptions of energy in first-year chemical engineering students (Ebenezer & Fraser, 2001), and to find levels of explanations, models and misconceptions in basic quantum chemistry (Stefani & Tsaparlis, 2009). In Engineering Education, phenomenography has been used to find student's variations in their understanding of conditional and repetition structures in computer programming languages (Bucks, 2010), their understanding of human centered design (Zoltowski et al., 2012) and designers understanding of the concept of design (Daly, Adams, & Bodner, 2012).

Because phenomenography has been used to study skills, and its extensive use in different fields, including research in engineering education, I considered it was a valid theoretical framework to design my study.

3.1.6 Data collection in phenomenography.

The typical method for data collection in phenomenographic research are semi-structured interviews. In these interviews, participants are posed in a state of meta-awareness about their practices, asking them to explain the meaning of what they did related to a specific situation lived by the participant before. In Marton's first, and in Bowden's approach, participants are asked about their experience with an object of learning. There is no activity that prompts participant's reflection on the topic the interviewer is asking about. However, it is assumed that this topic is familiar to the participant, and she/he would have an experience related to the object of study to share (e.g. Brammer (2006), Daly et al. (2012), Aflague and Ferszt (2010), and Zoltowski (2012; 2010). One or more participants with no experience at all with the object of learning could also be included in the research study, to contrast it with other conceptions that emanate from other participants with more experience, though.

In new Marton's, (and interestingly in the first Marton's studies at the end of the 70's), there is an activity related to the topic to be learned or a task to apply knowledge. This task allows them to bring in "conceptual tools (opening up dimensions of variation) for dealing with the example presented by the researcher" (Marton, 2014, p. 121), and participants are supposed to think aloud while dealing with the task. Typically, after that, the participants are interviewed about why they did what they did. This explanation allows the researcher to have more tools during the data analysis to differentiate the different dimensions of variation opened by the participants while dealing with the task. Complementary, researchers have also stated that other sources that can be used for data collection in phenomenography are: videos in which participants are recorded while acting (Marton & Booth, 1997; Wellington, Ward, & Armstrong, 2010), questionnaires (Chris Cope & Prosser, 2005), and other deliverables created by the participants that shows application of knowledge (Marton, 2014).

3.1.7 Considerations on quality (Validity, transferability, objectivity, reliability)

Sin (2010) collected the strategies that different authors have proposed to ensure quality in phenomenographic studies. In the following paragraphs, we will find how I instantiated these ideas to my study.

3.1.7.1 Validity

The main concern about validity is related to the source of the data: the interview. Authors cited by Sin said that there are differences between what people say and what people mean. In this respect, Marton said that, since we are trying to collect the dimensions of variation the participant opens to deal with the problem, it is possible that the participant decides to pretend she does not know, meaning she does not open during the interview the dimensions of variation we thought she would open. That would mean that you need at least one more participant within a similar range of previous experiences that you consider as key for your study. On the contrary, a participant cannot pretend they know, or that they can open dimensions of variation they haven't opened yet. This fact, and considering more than one people in a similar range of experiences, ensures the validity of the study.

Another validity concern regards on the fact that the study is performed by only one person. This was mitigated by weekly meetings with my co-advisors in which they play the role of the devil's advocate, kept challenging any finding I suggested. We iterated more than 15 times, and in every session, we engaged in dialogical conversations and co-construction of the understanding of the method, the different dimensions of variation, and the hierarchy among the different dimensions of variation.

3.1.7.2 Transferability

One of the critiques that phenomenography receives is about the non-generalizable results it has, or "the extent to which the findings obtained from a specific sample are representative of the target population" (Sin, 2010, p. 309). To address this critique, Sin (2010) proposes to, instead of considering the generalizability of the results, consider their transferability, "which is the extent in which findings can be used or applied in other contexts" (Sin, 2010, p. 309). The two alternatives suggested by Sin to ensure transferability of the results are: [1] maximizing the variation among the experiences participants have (Sin (2010) citing Larsson (1993)), and [2] considering the contexts in which the results could be used to include participants from these contexts.

Fulfilment of the two conditions presented above could be achievable by using purposive sampling "to have those [participants] that will yield the most relevant and plentiful data given … [the] … topic of study" (Yin, 2010, p. 88).

To make my study transferable, I maximized the variation on the level of experience addressing complex socio-technical systems. Therefore, I recruited novices, represented by undergraduate students from the first year to senior, and industry practitioners with less than 5 years of experience, mid-level practitioners with 5 to 20 years of experience, and expert practitioners with more than 20 years of experience. Additionally, by including engineering students, I am making my results transferable to undergraduate education, and by having participants from different engineering disciplines, the results of this study can be transferable across several engineering disciplines such as industrial engineering, aeronautical and astronmical engineering, chemical engineering, civil engineering, electrical engineering, and systems engineering among others.

3.1.7.3 Objectivity

It is difficult to bracket yourself in qualitative research, and especially in a second order approach such as phenomenography. As I will describe later, I did not bracket myself, but I used my knowledge as lenses to observe the data. However, I must also say that I allowed the data to speak, and that is why I did not look into the data specific topics related to systems, but instead, I was able to observe them in the data. It is also possible that some data was not meaningful to me, and it becomes meaningful for other researchers with a background in systems engineering. This is also related to variation theory. A researcher who has opened more dimensions of variation will observe in the data something different than one with fewer dimensions of variation opened. Still, I would argue that in my case, because of my training in systems, and my professional experience in industry, and as faculty, I am able to perceive several of the dimensions needed to address complex socio-technical systems. In addition, my two co-advisors whose experience is much higher in dealing with the method, and in dealing with real-world problems, helped me also to identify if what I was seeing in the data was valid, made sense and was useful. Having a team of co-advisors, and iterate with them more than 15 times, contributed significantly to ensure the judicious analysis of the data.

According to Sin, commitment to reflexivity, which is "when a researcher identifies his pre-conceptions and then systematically questions at each step how to minimize these effects is crucial for objectivity. Since I am not bracketing myself, to fulfill the requirements of objectivity, I engaged in a weekly iterative process with my advisors who played the role of devil's advocate, and, I kept a journal in which I documented my "journey" in this process. Therefore, I wrote several reflections on why I made some of the decisions, and my own perceptions regarding the step of the process in which I was at that time. Since the journal as it is, would be difficult to read by someone else different than me, I explained the process and used quotes from my journal in the data analysis section of this document. Having this document and the iterative process with my advisors satisfy the objectivity requirements.

3.1.7.4 Replicability

Replicability refers to the idea of the possibility of another researcher following the same steps to reach to the same results. Phenomenographers have said that this is difficult because it is a discovery process, and discoveries do not have to be replicable

(Marton, 1986; Sin, 2010), and that this idea is not appropriate for phenomenographic findings because it overlooks researcher procedures (Sandberg cited by Sin). You may find that this quote from Cope's dissertation (2000), citing Booth's dissertation (1992), has a strong argument against the possibility to replicate the results based on the fact that, as researchers, we cannot bracket our-selves either in the data collection, nor in the data analysis (2000, p. 85):

> Although broad methodological principles are adhered to, the open, explorative nature of data collection and the interpretative nature of data analysis mean that the intricacies of the method applied by different researchers will not be the same. Data analysis, in particular, involves a researcher constituting some relationship with the data. A researcher's unique background is an essential part of the relationship developed.
> Given this, replication of outcome spaces by different researchers is unlikely.

However, it is proposed that "interpretative awareness" and "maximum fidelity to the data" are two things that the researcher should achieve to show reliability in his/her research. The former, according to Sin, is similar in concept to reflexivity, which as explained above, was achieved by iterating with my advisors and by keeping a journal that explains my thoughts. The latter, maximum fidelity to the data was achieved by making decisions relying only in the data, which was domented in my Journal.

3.2 Research Design

In this section, I will show you the different steps taken in designing this study. In brief, I iterated three times with my interviews before starting with the formal process of collecting data, I did all the interviews, transcribed several of them, and iterated more than ten times with the data before having a satisfactory set of dimensions of variation and hierarchy among the dimensions.

3.2.1 Participants

In this study, I invited engineers with different levels of experience addressing complex socio-technical systems. I am assuming that professionals are all of those who completed their bachelor's degree. Accordingly, graduate students are considered professionals. Based on Davidz (2006), who found that experiential learning was a crucial enabler for systems thinking, I am assuming that with more years of professional experience, either in industry or academy, one gets more involvement or a higher understanding of the complex socio-technical system in which a solution will be, or at least some of the participants did have this higher involvement based on their experience. This higher involvement makes the learner open more dimensions of variation to allow people to address them, after these years of experience, in a more powerful way.

In total 25 people were recruited for this study. I invited undergraduate engineering students from different academic years, graduate students from different professional and academic backgrounds, industry practitioners with years of experience ranging from 1 to more than 20, engineering faculty with experience ranging from 10 to more than 20 years of experience, and one management scientist who according to my records, had a strong systems thinking background and knowledge.

3.2.2 Ensuring quality: Validity and transferability

First, I will describe the sampling strategies used, as part of my argument for the validity of my study. Undergraduate students were recruited first randomly, and then by selecting candidates that could be very different from each other. Unfortunately, not all those selected attended to the interview, and at the end, I was able to complete 10 which was deemed sufficient for the study of the variation needed. Graduate students, faculty professors, and industry practitioners were also recruited using a purposeful sampling strategy to be sure I was maximizing variation in the sample.

To ensure gender balance, in the results, I made sure that there were a similar number of men (12) and women (13). Likewise, to fulfill the requirement of transferability, I invited people with different nationalities and races. 15 people were born in the US, one (1) was born in Europe, six (6) people were from South America (five from Colombia, one from Argentina), one (1) was from Africa, and two were China. All undergraduate students were from Purdue to facilitate IRB approval. 15 people were white, one was an African-American, one was African, 7 were Latino American, and two were Asian. For more on the fulfillment of transferability, my participants were from different fields: Undergrads were from acoustical engineering, Aeronautical and Aerospace Engineering, Biomedical Engineering, Chemical Engineering, Electrical Engineering, Engineering Management, Industrial Engineering and Mechanical Engineering. Professionals were from Management, Aeronautical and Aerospace Engineering, Chemical Engineering, Civil Engineering, Computer Science, Construction Engineering, Electrical Engineering, Engineering Education, Environmental Engineering, Human-Centered design, Industrial Engineering, and Mechanical Engineering.

Regarding their experience, undergraduate students recruited were two from the first year, one from the sophomore year, five from the Junior year, and 2 were Seniors. In respect to professionals, 1 had one year of experience, two were between 1 and 5, four had between 5 and ten years, three between 10 and 20, and 6 had more than 20 years of experience.

Undergraduate students also had diverse experience in Engineering Projects in Community Service - EPICS, Global Engineering program, Community service, Professional Internships, Jobs related and not related to their engineering field inside and outside of campus.

All this variation satisfies the validity requirement of having at least two participants with similar levels of experience. It also fulfills the requirement of transferability across different engineering programs, and going beyond the academy, to consider this results valid also for industry.

3.2.3 Data collection instrument design

3.2.3.1 Survey to capture variation

I developed a survey to capture the variation of professionals and students (see Appendix 01 – Data collection instruments). The survey for professionals had 32 questions, and the one for students had 19. In Table 3.2 you can find the types of questions, and the full interview, in Appendix 01. Both, students and professionals were also supposed to address an inventory personality test, also known as the big 5 (44 questions seeking to rank participant's openness to experience, consciousness, extraversion, agreeableness and neuroticism). Additionally, the participant was required to complete the Person – Thing Orientation test (13 questions to determine a score in each dimension for thing orientation and a score for person orientation). This personality section was adding in total 57 questions. Accordingly, a professional was supposed to answer 89 questions, while an undergrad 76 questions.

Table 3.2 - Types of questions asked to capture participant's variation

Description	**Students**	**Professionals**
Doing extracurricular activities in high school	X	X
Involved in EPICS or Global Engineering Program or Service learning or any social internship and time of involvement.	X	X
Participation in extracurricular activities while in their Bachelor's degree.	X	X
Other learning environments the participant had to apply skills not taught in the classroom.	X	X
Participant has done a co-op or has had any other job while doing their undergrad studies explaining the kind of work experience the participant had.	X	X
Academic experience beyond undergrad studies		X
Being taught about systems thinking (and time)	X	X
Being involved in Public policy definition	X	X
Time of involvement dealing with complex problems	X	X
Change of perspective/ change of domain of knowledge	X	X
Leadership experiences (e.g. have you lead a project? When dealing with these complex problems?)	X	X
Time of involvement as a leader	X	X
Work as a graduate student?		X
Formal or informal training in systems thinking	X	X
Complex problems in their professional practice		X
Profession		X
Gender	X	X
Etnicity	X	X
Age	X	X
Years of professional experience		X
Residence status	X	X
Primary Department	X	
Years to get graduation	X	
View of their discipline	X	X

3.2.4 Interview design

I developed two different interviews for this study, one to test the style of interviews proposed by Bowden, and another one to test the style proposed by Marton (Appendix 01 – Data Collection Instruments). Consent forms for participants who are students and professionals were also developed to pilot the whole experience of the interview (In Appendix 01 as well). These two interviews and consent forms were also translated to spanish in case the participant's first language was spanish. Participants whose first language is not english, but also is not spanish, will answer the interview in english.

3.2.4.1 Interview design following Bowden's approach

In Bowden's approach, people are asked about their experience or understanding about a topic X. In this case, I asked them about their experience addressing complex socio-technical systems using the term "complex problems," which is a term use more commonly by people and is found in several books. There was no intention of giving the participants a common context. The survey started with a rapport to create a connection with the participant. After that, three questions were posed looking for participant's reflection about the way they experience the topic:

- Please tell me now about a successful experience in your past when you had to deal with a complex problem.
- Tell me what is the most difficult Problem or Project that you have ever faced in your professional or personal life? In case that's the one you just told me, consider another one with high difficulty.
- Please describe one less-successful experience in which you had to deal with a complex problem.

The first two questions were focused on making participants talk about their experience (what they do):

- Would you say that it was a complex problem?

Note: If the interviewee says yes, ask: Why is that?

- With your current knowledge, how would you go about that problem today? How is it different to what you did in the past? How the story of yourself would be dealing with this problem, walk me through the whole process with as many details you can. Tell me for example, the strategies you would use to understand/ make sense of the problem, also where would be the difficulties and how would you faced them, etc. While you tell me the story, please contrast it with what you did.

Probe questions were also prepared to get a meta awareness of their experience, or what is also called a “second order thinking” or “thinking about thinking.” They were asked, depending on the moment of the conversation questions like:

- What would lead you to do things in that way? Why would you do that? How did you decide that you would do these things? Why did you make these decisions? What did you gain or hope to gain from it?
- In your thinking about how to go about this problem, what kind of things related to the problem would you consider to analyze it or learn more about it?

Since the goal was to dig deeper when the participant mentioned a particular characteristic of systems thinking. I proposed the following guide to dig into those ideas:

Note: the interviewee may talk about one of the following items found in the literature. Since they are considered key for understanding the level of systems thinking, the interviewer should dig into these topics:

- Componential elements considered in systems thinking like behavior, form, purpose/objectives, performance, data, management and the balance between social and technical components (Davidz, 2006) or the elements of public policies or organizational issues.
- Considering the dynamic interaction among the different elements taken into account in the problem, or the feedback processes, or the uncertainty, or the risk.
    - For processes that were changing at the same time ask: How did you know that these processes were interrelated and were changing at the same time? Why they were relevant? Why did they contribute to making the problem more complex?
    - For events in the past that impact the current and future situation: Why was it relevant for you to consider these events?
- Relations: Why is it relevant to consider interconnections/interactions/interdependencies within the system and with the system with other systems? (Interviewees could use a different word than system)
    - How did you determine the limits of the problem? What was the process of defining the criteria to choose what things were relevant and what weren’t?

- Were you able to directly intervene in the problem solution? What and how did you do it?
- Why did you do those things?
- What leads you/motivate you to make those decisions?

Once the participant provided an answer for the problem, I asked two reflective questions to the participant at the end of each. These two questions have the goal of making the participant aware of the meaning of his/her experience:

- Please tell me what kind of tools or skills did you use to approach this problem?
- How would you define the skill that is needed to deal with complex problems that I call Systems Thinking?

Being able to see analogies between systems is one of the characteristics related to systems. One question asking for analogies was prepared:

- How the experiences you describe are similar and how they are different?

Finally, one question asking for participants meaning of system's thinking:

- What would be the definition of systems thinking, the skill that is required to deal with complex problems like those that you have described in this interview that I call Systems thinking?
- How do you use systems thinking to go about complex problems?

3.2.4.2 Interview design following Marton's approach

I was seeking to have a way to "see" or understand what the participants were "seeing" or "thinking," based on what the participants were going to be asked to "do", or "say." To help my participants say what they were thinking, I asked them to follow a think-aloud protocol. The reason why is explained by Ericsson & Simon: when people are asked about their thinking, they may going “beyond merely verbalizing spontaneous generated thoughts, to produce the thoughts that would contain descriptions and explanations… [and] are likely to alter the course of thinking ”(1998, p. 181). Accordingly, the interview had two steps. In the first one, the task was given to the participant, and she was asked to think aloud while addressing it. The participant was asked about their thinking some times. The interview will start with a rapport, then a practice of the think-aloud protocol, and after that, the participants was asked to complete five tasks. Once the participant finished the task, she was asked deeply about what she did. You may be wondering what and how did I define the task. I am presenting in the following paragraphs.

<u>Tasks Designed for using Marton’s approach</u>

The crucial idea in new Marton’s phenomenography is that all the participants have the same experience, or “see the same thing”. The role of the researcher is to find variation among the background of sameness provided by having the participants addressing the same task.

The characteristics of the tasks in phenomenographic studies that I included when defining the criteria for choosing one over the other are (Marton & Booth, 1997):

1. They “have to be novel and open-ended” (p. 106). Because of these characteristics, the participant can “open up dimensions of variation as she finds it necessary” (p.106).
2. The questions asked have to be “rather simple and straight forward, and neutral concerning the difference between every day and scientific conceptualizations (it should be possible to answer them from either perspective)” (p. 108). In this research,

the simplicity will be understood as if the participant understood what the goal of the task is, and what they were asked to do.

3. The questions should not point out the relevant aspects of the problem to be solved. (p. 108)

In a personal correspondence with Marton held at the beginning of 2014, he suggested me to have at least two different tasks. This idea was because it would help me to to separate the ability a participant may have developed addressing similar tasks (which may make her look like an advance participant in the skill), from the general abiltiy to deal with the problems in enginering complex socio-technical systems. I found the value of this advice later when I was peforming data analysis.

It was necessary then to find two different tasks that fulfill the criteria proposed by Marton, and that also elicit systems thinking.
In addition, the task should ask the participants to address a problem in a complex engineering socio-technical system. Accordingly, I added the criteria "represent an 'authentic design task' or an engineering task, or both, in a complex engineering socio-technical system."

The ability known as "graphical integration, is basic to understanding the dynamics of complex systems" (L. Sweeney & Sterman, 2001). This ability, as explained by Sweeny and Sterman, as the need a learner has to be able to determine "how the quantity of a stock varies over time given the rates of in and out of the stock." It is also necessary when creating a graph that tells a story about the behavior of a system.

Accordingly, a task that promotes graphical integration in the participants became another criterion for selection.

There are different tasks that have been proposed in the literature to teach or assess systems thinking. I have chosen the following four: coffee challenge (Purzer, Ş. & Wertz, 2013), wolves and sheep (L. B. Sweeney & Sterman, 2007), the manufacturing case (L. Sweeney & Sterman, 2001), and the disaster relief scenario (Adams, Beltz, Mann, & Wilson, 2010); and I created one more: scene it.

The two tasks from Sweeney and Sterman were, according to the authors, designed to elicit in participants their knowledge about key concepts in systems dynamics: awareness of dynamics, awareness of accumulations and flows.

- Wolves and rabbits (L. B. Sweeney & Sterman, 2007): This task is mixing two concepts. First, it was designed to "surface conceptions of cause-and-effect relationships and behaviors that can feedback to form reinforcing or balancing processes" (L. B. Sweeney & Sterman, 2007, p. 289). Second, the use of simulations to learn about complex systems (Sterman, 1994), and to make participant use his/her mental model so I can have some evidence of his/her way of thinking(J Doyle et al., 2008; JK Doyle, 1998). NetLogo developed the simulation, and it is available online(Wilensky, 1999, 2005). The task was slightly changed to fit the simulation, so instead of wolves and rabbits, we ask for the relationship between wolves and sheep.
- The manufacturing case (L. Sweeney & Sterman, 2001): This task was one of three designed to assess "student's baseline systems thinking abilities … and was designed to be simple and in a way that can be answered without the use of mathematics

beyond high school" (L. Sweeney & Sterman, 2001, p. 252). About the manufacturing case, the authors explain that:

> assesses student's understanding of stock and flow relationships in the presence of a time delay and a simple negative feedback loop … [it] also test the ability to create graph that tells a story about a particular behavior over time, and to draw inferences about the dynamics of a system from a description of its structure (L. Sweeney & Sterman, 2001, p. 257)

The next one is a design task that was developed to scaffold "student knowledge and skills in information seeking and documentation by modeling and discussing a written example"(Purzer, Ş. & Wertz, 2013, p. 190). Besides, it was also used in fall 2013 in the first year engineering program at Purdue, when students were introduced to the concept of "whole systems design" (related to sustainable design):

- The coffee challenge: (Name used in First Year Engineering: The coffee maker challenge): This task asks students to develop an energy efficient coffee maker machine. In my experience using this activity in fall 2013 with my students of first year engineering, I noticed they get focused on the coffee maker machine developing ideas for solar cells feeding power to the coffee maker and using recyclable materials. I modified the problem from emphasizing the need to create an energy efficient coffee maker to making a cup of coffee using the minimum non-renewable energy. With this exercise, I wanted to see if participants can see beyond the process of making coffee, either with a coffee machine or without it. Besides that, if they enhanced their vision beyond the coffee maker, this activity may show if participants opened different dimensions of variation than those that are already opened by first year engineering students. Would participants with higher expertise thought about any dynamic behavior, would they be aware of feedback processes, would they think about public policies and other regulations? Would they recognize the challenge as a problem in a complex engineering socio-technical system?

The fourth task is another design task that was proposed in the context of sustainable design and was used to assess how students formulate cross-disciplinary sustainability problems (Adams et al., 2010). These authors were also assessing cross-disciplinary systems thinking. I used this task to include in the study problems that could arise in organizational systems design and to see how far participants get when conceiving solutions for organizational design problems. Authors also stated that this problem can link technical, environmental, social, economic and political perspectives, similar complexity that engineers will or currently face in their professional practice that makes it a problem in an engineering complex socio-technical system.

- Disaster relief scenario task (Adams et al., 2010): In this task, participants are asked to design a “disaster response system ” for tornadoes in Tippecanoe County, Indiana. Since one of the dimensions of variations is fulfilled by having participants from different parts of the world that may not have lived in a place where tornadoes are common as the United States. I change the problem from tornadoes to flooding since flooding is a natural phenomenon that could and have happened in countries all around the globe, it is probable that participants have a close experience that can help them to build a strategy.

The final task of these set, follows the philosophy of the box game “Scene it?” In this kind of games, a scene from a movie is played and after that, participants are asked about the next scene. In this task, I chose a scene from the "Bruce Almighty" movie staring the actor Jim Carrey. There, the main character gets the same powers and responsibilities of God, but he does not receive his/her wisdom. One of the possible interpretations of the plot of this movie is that the main character does not do a good job as God because of his low levels of systems thinking, which means a lack of consideration of the lon-term when making decisions. In the scene I chose for the task, the main character, to seduce his wife, brings the moon closer to earth. The main character could not see beyond his view of the world, and the linearity of his thinking made him blind to unexpected consequences that arisen because of the relationships between the parts, called emergence. Moon and earth have a feedback loop relationship that avoids them to hit each other. Also, there are elements of earth that are related to the moon like the tides. This exercise intended to reveal if the participant can perceive outcomes that go beyond the short-term cause effect relationships. Likewise, if they were aware of dynamics, time delays, the use of conceptual models and maybe, their vision could reach the need of new policies to tackled the problems that could arise as a consequence of making the moon closer to earth.

3.2.5 Pilots

The pilots are necessary for instrument calibration and were used in this study to refine the interview protocol and procedures with the tasks. In qualitative research, the instrument of data collection is the researcher. It was crucial to develop my skills as an interviewer for phenomenographic research, and also to develop the ability to ask participants questions in which they unveal the dimensions of variation they were opening to address the task. To get this training, I followed the recommendations provided by Akerlind (2005) and Green (2005) about the need of piloting the interview and perform a critical reflection to improve the researchers ability to ask the right probe questions and avoid including new ideas or statements that were not said by the interviewee. In this process, I asked Dr. Cardella, one of my advisors, to interview me using the interview protocol I designed. I learned from this experience that the probe questions don't have to be complex.

Running the pilots was also necessary to have more arguments in favor or against choosing new Marton's and Bowden's approach. They were also crucial to choose the final two tasks among the five proposed when following Marton's approach. In the following sections, I will present my experience piloting the survey and the interviews

3.2.5.1 Pilot 1: Survey to capture participant's variation

After piloting the survey, the common feedback I received was that it was "too long" and also that the variation I was trying to collect was "too broad". I received that feedback in a meeting with my research group, and from one friend that accepted my invitation to be interviewed so I could pilot both instruments.

After receiving the feedback, I revised the work from Davidz (2006) where she defined the enablers for systems thinking. Since the dimension "experiential learning" was the one ranked first as an enabler in her research. Since I was asking too many questions, I make it shorter. I also revised the instrument used by Atman et al., to capture their participant's variation (Atman et al., 2007), and I used it to make the survey shorter. I also cut out the individual characteristics questions Davidz did not define a significant correlation between these traits and systems thinking. In Table 3.3, you will find a description of the different types of questions I asked participants to be sure they were different from each other.

Table 3.3 – Description of different types of questions asked to participants to make sure they were different from each other

Dimension	Kind of experience	Professionals	Students
Work on diverse things (Broad experience)	Participants who have been in the same company/Project playing different roles, or participants who have been in different jobs and different companies.	Participants who have worked in industry and academy. Participants who have been in different roles.	All engineering students at Purdue students have developed projects in teams since the FYE program, or the Honors program is a requirement for all of them. Students who have been involved in at least two different kinds of curricular activities like EPICS and an engineering contest.
Systems/jobs experiences	Participants who have been developing a solution in interdisciplinary teams (it was necessary for them to see the big picture of the system) or participants who use or teach systems thinking.	Professionals with different experiences related to systems. For example, academics from different fields and years of experience that in that in their jargon use the word system. For instance aerospace engineers and biologist. Academics who have taught systems thinking with different time of experience.	e.g. Students from Global Engineering Program, EPICS with different number of semesters of involvement
Familly, early life experiences	Being raised in different cultures	Professionals from different fields in STEM and Management born and raise in the US and other countries. For example Asia, Europe, Latino America, Africa and Australia.	Domestic and international students.
Supportive environment	Have tight time constraints and narrow job		

In Table 3.4, I will be matching the set of questions with the dimension they are related and if these questions will be directed to students or professionals

Table 3.4 - Match of questions with dimensions, and who was asked

Question	Dimension	Students	Professionals
What is your ethnicity?	Familly, early life experiences	X	X
Did you do your first years of education outside of the US?	Familly, early life experiences	X	X
How many years of professional experience do you have?	Work on diverse things (Broad experience)		X
What is the highest level of study you have achieved?	Academic systems experiences	X	X
Briefly, describe two of the most difficult/challenging complex problems you have faced in the past.	Systems/jobs experiences	X	X
Grade your agreement with the following sentence: I have been involved in the same company/project for a long time doing the same job or performing the same role.	Work on diverse things (Broad experience)	X	X
Grade your agreement with the following sentence: I have been involved in the same company/project for a long time in different positions/roles.	Work on diverse things (Broad experience)	X	X
Grade your agreement with the following sentence: At least in 60% of my job/projects, I can be creative and failing is safe.	Have tight time constraints and narrow job	X	X

3.2.5.2 Pilot 2 – Piloting Bowden's interview

I recruited two participants for this pilot. To protect their identities, they will be called Christie and Laura

Table 3.5 – Description of Bowden's pilot participants

Characteristic	Participant 1: Laura	Participant 2: Christie
Gender	Female	Female

Ethnicity	Multiracial	Latino/hispanic
Country	The US	Colombia
First years of education	In the US	In Colombia
Highest level of education achieved	Master	Bachelor's
Years of professional experience	Not determined	More than 10
Complex problem in the past	Rotor blade design problem	Definition of the presidential program in Colombia

The interviews were run in November 2014 and were transcribed by me. As stated above, these two interviews were completely different, and it was challenging for me to think of a common aspect or feature between the two participants.

3.2.5.3 Pilot 3 - Piloting Marton's interview

Following Marton's idea of having as much as possible a background of sameness to be able to find the variation, I asked the same two participants I interviewed following Bowden's approach if they would like to be interviewed again. They accepted the invitation, which allowed me to compare the two interviews having the same tasks, and the same participants. While running the interview, and while reading the transcripts, I was able to identify topics in which they were talking about the same thing, but describing it differently. For example, in the "scene it" task, Laura decided to focus her attention on the inability the main character might have to have a good use of his power. She also discussed other similar movies and roles that Jim Carrey has had in other movies. She did not focus on the scene. On the other hand, Christie decided to talk about the possible impact that, moving the moon closer to earth could have on earth's ecosystem. The last comparison I will cite is brought from the disaster relief scenario problem. In this case, while Christie thought about three different moments in which an emergency could have been addressed (before, during and after), Laura focused on designing a system for prevention.

After these pilots, I had theoretical support for choosing new Marton's approach for data collection as well as pragmatic support and evidence from the data of the transcripts.

3.2.5.4 Tasks analysis to choose the two tasks that will be used in the interview

Now that I was sure I was going to use Marton's approach, it was necessary to evaluate which tasks, among the 5, were best for achieving my goal.

I evaluated the effectiveness of the tasks by giving scores from 0 to 5 to the following criteria: [1] Novelty, [2] simplicity of the question, [3] if the task could be considered as a problem in an engineering complex socio-technical system, or [4] if it was an authentic design task (2.5 each), and [5] if the task elicits in the participants what is called graphical integration (graphs that tell a story about behavior over time).

The evaluation of the tasks considered a score of one per each new way of dealing with the task that was opened by participants. If the two subjects dealt with the task using the same strategy, it counted as one way.

Finally, I considered if the task elicited systems dynamics concepts in participants, which is relevant because systems dynamics is a relevant topic in the systems literature. There are also proposals for effective teaching and assessment of systems dynamics, which are always connected with the ability I am studying in my dissertation.

After evaluating each task based on the criteria proposed, the tasks receive the following scores: Manufacturing case (22.5 points), wolves and sheep (21), disaster relief scenario task (17.5 points), coffee challenge (16), scene it (16). Since the wolves and sheep task is not an engineering task, neither a design task, and it shares several features in structure with the manufacturing case, I chose the next task, the disaster relief scenario. This task, according to what I saw in the pilots, potentially can open more dissimilar dimensions than the one from the coffee challenge, which also score lower.

A detailed analysis of each of the five tasks is shown below.

Task 1 - Scene it. The participant was asked about the next possible events that would happen after a scene of a movie. The total points this task got was 16.

Table 3.6 – Assessment of task 1. Scene it.

Criterion	Assessment of task 1	Score
Novelty	This task was novel because it was asking them to do something they do not do in their everyday routine.	5
Simplicity of the question	The question had two components. First, the person is asked to watch the sketch, and after that is asked: "what would happen next?" Participants did not have any problem understanding the question, and they did not report as being pointed out to any relevant aspect of the problem.	5
Dimensions opened in the pilot by participants (ways of dealing with the task)	Christie dealt with this task by considering a bigger picture beyond the three elements presented in the scene (The girl, Bruce (Jim Carrey) and the moon). Laura focused her attention in the moon and did not mention Bruce and his wife again. When focusing on the moon, she considered its relationship with Earth (which could be considered as a partner system regarding Herrscher (2003) and with elements on earth (can be understood as sub-systems of the Earth) like the tides). Besides, she observed that these relationships could be non-lineal. Aspects that she was able to see: Christie talked about the equilibrium (balancing feedback) between the gravities of the moon and earth, interrelationships. "incluso lo que hizo podría hacer que la luna se estrellara hasta con la tierra porque hay un balance entre las gravedades de la tierra y la luna, donde si ese balance se pierde, la luna incluso puede matarnos … En la naturaleza hay un equilibrio donde todas las cosas están relacionadas e interactúan unas con otras y si hay alguna que se afecta el resto se afecta" She also talked about non-linearity and time delays, by saying that all members of an ecosystem are related to each other directly or indirectly and sometimes the impact is not immediate or easily seen: "todos tienen repercusiones los unos sobre los otros, aunque inmediatamente no se vea"	3

Criterion	Assessment of task 1	Score
	Another possible dimension that Christie opened was the use of a homology to explain her point: small fish in the ocean that was eaten by a foreign specie causing large impacts in the ecosystem, such as contamination and disease: “Unos pecesitos muy pequeñitos que ... En el mar .. Como unos microorganismos que se encargaban de limpiar los corales y de limpiar el mar, un día hubo un desequilibrio en esos organismos porque llegaron unos peces, porque hubo sobrepoblación de peces y esos peces comían de esos animalitos, entonces se disminuyó la población, entonces eso hizo que esos pecesitos dejaran de limpiar tanto el mar como lo limpiaban y eso causo que todo el ecosistema donde estaba el resto de peces se volviera más sucio y contaminado y muchos de los otros peces murieran a raiz de eso” Laura dealt with this task by considering the bigger picture. Unlike Christie, Laura though about the plot of the movie, and about analogous characteristics of movies in which this actor participate: Laura focused on the plot of the movie and how the main character would face difficulties because of the power he has: “based on the nature of this film clip, he is looking for the successful seduction of this woman, probably won't end up being successful, because of the possible abuse of powers.” Here we see other two dimensions related to the movie. By seeing the plot, the participant shows evidence that she is looking for the big picture, focusing on the movie. The following quote shows how Laura is also thinking about other movies with the same actor and categorize them, because of that, as funny. In this case, she is dealing with the task using homologies: Jim Carrey knows how to do funny. Uhm... In the 1990's cause, I would have been when I was in middle school that he first appeared on the movie scene, and they were all comedies Laura also used homologies to think about the plot and possible ending of the movie: Having extraordinary powers come as the Midastouch, the ancient Greek story, yeah he had this Midas touch, then when you want to eat, all the food you touch turns to gold, so it has been a curse rather than a blessing. I am gonna guess that at somepoint this appera this probably write about this moment in the film, that his blessing and suddenly become a curse on him. A number of dimensions: I identified three ways of dealing with the task, one was by homology and the other two by considering the big picture. It is relevant to say that Christie’s way of considering the big picture is richer than Laura’s regarding some critical aspects she discerns. That is why I consider it as another way.	
Engineering task / “Autenthic design task.”	There are no considerations of design in this task.	0
Participants show graphical integration - graphics that tell a	No, no graphs were created by participants	0

Criterion	Assessment of task 1	Score
story about behavior over time.		
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	Three elements were mentioned: time delays, negative or balancing feedback, and draw inferences about a dynamic of a system from its structure	3

Task 2. The coffee challenge: the participant is asked: "There is a coffee house chain that is asking for advice on how to reduce the amount of non-renewal energy they use to make its coffee, so they can tell its customers that its coffee was made with the fewest (least) amount of non-renewal energy possible. What elements would you advice the company to consider to achieve this goal?" the total points this task got was:16

Table 3.7 – Assessment of task 2 – The coffee challenge

Criterion	Assessment of task 2	Score
Novelty	None of the two participants expressed they have done something like this in the past. There could be an issue because some engineering students at Purdue may have developed a similar task in their ENGR131 course. However, this task is slightly different, and because time has passed, students may not remember it completely, and if they do, the change in the wording to the task may help to hinder the relationship with it.	4
Simplicity of the question	Christie asked for clarification on what the non-renewable sources of energy were. She also asked if we had budget limitations. Besides that, there was no need of further clarification. These questions are not showing that the question is not understandable. In the case of Laura, she understood the problem and started the conversation immediately.	5
Dimensions opened in the pilot by participants	Christie dealt with this task considering a big picture in which several subsystems are interacting to produce the coffee cup. She identified the production and manufacturing system that produces the coffee and the one that packages, the administrative system, the environmental system (petroleum), the supply chain system, and the customer system. Reduction of energy usage is seen by Christie as efficiency in energy consumption. She proposed a mixed technique of	2

Criterion	Assessment of task 2	Score
	reducing the amount of energy while producing coffee and reducing the amount of materials that use non-renewal energy sources such as plastic (because it is made from oil). She proposed to change it for paper (which is biodegradable), and to reduce the amount of paper they used (by going digital as much as possible): Buscaría que mis máquinas del proceso fueran las más eficientes a nivel de energía posible … El empaque del café sea el mínimo necesario …en lo posible, trataría o evitaría usar plásticos, porque esos son derivados del petróleo, trataría de usar papel porque es biodegradable, en mi misma empresa trataría que todo sea digital She added that a reduction in the fuel could be made by hiring local distributors so the company can save in transportation cost and also reduce the amount of oil used for coffee transportation. Tendría distribuidores locales para minimizar también el costo de transporte y el uso de gasolina Christine also talked about changing customer's behavior by telling them to use washable coffee cups instead of plastic ones. Usen pocillos que se puedan lavar en lugar de desechables. One way in which Laura dealt with this task is using a homology. In this case, the homology is a coconut candy factory she had visited in the past. The aspects in which she focused her attention when trying to reduce the energy consumption were: Laura saw a reduction of energy use as using all the raw materials and produce minimum residuals. Two examples were provided: So we visited an island where they make coconut candy, and we visited their whole manufacturing facility, coconuts come with a quite thick husk, right? So they would husk, de-husk the coconut and they would use all of that for firewood. Ok. Then, they would extract the water, from the fresh coconut, and then they also extract the ... There is like the nuke flesh, that's inside the coconut, so they would have a shave. That now and then they would press that, to get much denser coconut milk. So coconut water, coconut milk, then error, so they may have also use the flash to make an extremely sticky coconut candy, but I was most impressed by the fact that none of the coconuts was wasted because they need to be boiling the water and the flesh to make the candy, so they use the otherwise useless husks as their heat source I would ask the coffee company how much control do you have over the whole production line, the beans that are grown, the leaves that go with it, any of these byproducts that the plant itself might produce that's not the bean, how could you actually use that in a same or similar form like the coconut candy place	

Criterion	Assessment of task 2	Score
	Seeing the big picture (or doing a zoom out “to look at the macro level”) to analyze the life-cycle of the product from “cradle to grave” is another way that Laura used to deal with this task. She said this is relevant because it enables her to think about “other stuff you don’t see, don’t think about”: Instead of just seeing what happens at the counter, between the customer and the person selling coffee, but to zoom out at whole production process, and let's talk about the plants, let's talk about the land, lets' talk about the tools, let’s talk about the transportation of the vegetable product to and from their facilities. Cause that's to get all of the human labor, all that natural renewal resource and even the non-renewal resources, all of that produces that cup of coffee, and not just “am I using a paper cup or a glass cup or a cup you bring from home”, but also the trucks that bring us here, the people that bring it here, uhm, all of those aspects as well, non-probably not enumerating all of those, but when we are looking just a larger socio-economic division of human labor. Uhmm. You can start to claim I am reducing what the (the field from where the participant is coming from business we call cradle to grave. So cradle to grave mindset seems to be the burden of the manufacture # of dimensions opened: Christie and Laura’s approaches to the task doing zoom out to see the big picture will be considered as one way. Using homology will be another way. This problem opened two dimensions of dealing with the task.	
Engineering task / Authentic design task	Participants thought about different alternatives to change the current status quo of the company, which represents engineering work. According to the criteria for an authentic design task proposed by (Adams et al., 2010), this task fulfills mostly the characteristics of an authentic design task.	5
Participants show graphical integration – graphics that tell a story about behavior over time.	No, no graphs were created by participants that were used to explain behavior over time. For example, explain the behavior of company sells over time.	0
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	None of the elements were clearly identified from the answers of the participants.	0

<u>Task 3. Wolves and sheep</u>: the participant will explain the relationship between wolves and sheep. The first part will ask them to explain it based on their knowledge. In the

second part, I presented a simulation with starting values of 100 sheep and 30 wolves, asking the participant what she sees. The average points the part A and B got was 21

Part A – Without simulation – Points obtained: 21

Table 3.8 – Assessment of task 3 – Sheep vs. Wolves without showing the simulation of the case

Criterion	Assessment of task 3 without	Score
Novelty	None of the participants mentioned that they knew this task before. However, one of the participants (Laura) mentioned that she studied something similar in her class of systems dynamics.	5
Simplicity of the question	Laura asked if the sheep were eating if there were unlimited food supply. Christie asked for confirmation about the place in which the wolves and the sheep were (on an island). Both of them were able to understand what to do.	5
Dimensions opened in the pilot by participants	The way in which Laura dealt with the task is by transferring her knowledge about the behavior of dynamic systems to the current problem. She reasoned by homology. In this case, these homologies are drawn from systems dynamics, showing understanding of systems behaviors and principles. Important information for Laura was: reproduction rate and consumption rate. Laura talked about dynamic systems that look for equilibrium. For her this system will find equilibrium as is “everything in nature.” We have a tendency as humans to design dynamic systems, and we have a tendency to overshoot some equilibrium state in the [inaudible] out, that some equilibrium stat, we design it that way, nature has a tendency, not to overshoot, as it approaches equilibrium, seem to me nature is pretty well damped to get to some equilibrium. She also identified that was important to consider input and output rates as function of time: but I know that there are equations that do that, that balance the two input output rates, and it shows me as a function of time what the equilibrium state would be because is a naturally damped System ... Christie dealt with this problem intuitively, using her previous knowledge about sheep and wolves and ecosystems. For Christie, important information was related to the amount of food the sheep could have. For her, the two populations will die; first, the wolves would eat all of the sheep, then they would die of starvation or die because they eat each other:	2

Criterion	Assessment of task 3 without	Score
	no creo que la rapidez de reproducción de las ovejas sea lo suficiente para mantener la población de los más que tu dices que son 30 lobos, entonces, como tú dices, va a llegar un momento en el que las ovejas van a desaparecer The reproduction rates that she considered are focusing on the sheep. She did not mention the reproduction rates of wolves.	
Engineering task / Authentic design task	This is not an engineering task neither a design task.	0
Participants show graphical integration - Graphics that tell a story about behavior over time.	Laura used two graphs to explain the behavior of a damped system, which is a system that oscillates, before reaching a steady point.	5
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	In the previous quotes, you can find that participants talked about stocks and flows, identified negative feedback, drew inferences about the dynamic of a system from its structure. The following quote shows that Laura also thought about time delays: because sometimes like we think of grey sharks as predators, but they only eat like, every three days, so then … they may give their pray **time to catch u**p if they reproductive rate is greater than the consumption rate, then also the reproductive rate of set predators so that part matters	4

Part B with simulation. Points obtained: 21

Table 3.9 - Assessment of task 3 – Sheep vs. Wolves showing the simulation of the case

Criterion	Assessment of task 3 with simulation	Score
Novelty	None of the participants mentioned that they knew this task before.	5
Simplicity of the question	None of the participants mentioned problems understanding what to do.	5
Dimensions opened in the pilot by participants	In this stage of the task, the two participants were consistent with their way of dealing with the task described previously. Laura transferred her knowledge from systems dynamics, and Christie used her intuition. Laura expected to see a damped system: I am expecting a trace that eventually overtime dampens, for both of them. And I am not seeing that. … So it's not damped as it should be. Is almost impossible to have an undamped system on planet earth, because friction always exists, you put all of those in the different type of system hydrolical, electrical, transitional, rotational all of these systems they are gonna	2

Criterion	Assessment of task 3 with simulation	Score
	be dampening, it's a fact of life, having an undam system as this simulation shows, is not realistic Christie identified a repetitive cycle. She described what happened in the system according to the graph and mentioned the interaction between the two species. According to her, they are correlated since one affects the other. Aquí lo que se ve es un ciclo repetitivo, cuando la tasa de mortalidad alcanza la misma que la tasa de mortalidad de las ovejas, la curva empieza a cambiar de nuevo, entonces es cuando vuelve a haber otro punto de equilibrio, donde hay suficientes ovejas para los lobos existentes, y después vuelve y sube otra vez la población de ovejas, la de lobos disminuye un poquito más, como se vió incluso en la anterior gráfica … digamos que los dos tienen una interacción muy cercana porque cuando el uno va aumentando, el otro va aumentando y llega un momento en el que otro disminuye lo suficiente y afecta al otro, y el otro también empieza a disminuir.	
Engineering task/ authentic design task	This is not an engineering task. It is not an authentic design task either.	0
Participants show graphical integration. Graphics that tell a story about behavior over time.	Laura used two graphs to explain the behavior of a damped system.	5
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	Stocks and flows, negative feedback, ability to draw behavior of a system from its structure can be seen in this quote: No, the moment the wolves' population dues to (reaches) zero, assuming an unlimited food supply, sheep do die, uhmm some trying to explain, why a population would comeback now, population that comeback now, based on .. Unlimited food supply for the sheep, should the wolves' population go to zero. So that's what I'd be expecting... So still relates back to consumption rate and reproduction rate, with knowing that it takes at least two of either one to allow the population to increase again. In the first quote from Laura, we can also see time delays.	4

Task 4. The manufacturing case. This task is talking about managing the inventory of a product in a company. There are input and output rates, and a change in those rates. The participant is asked to describe the behavior of the inventory after the change. Points: 22.5

Table 3.10 - Assessment of task 4 – The manufacturing case.

Criterion	Assessment of task 4	Score
Novelty	None of the participants mentioned that they knew this task before. A task involving dealing with inventories could be common in different disciplines like management, industrial engineering, systems engineering, accounting, etc. However, this task was design to assess four dimensions of knowledge related to systems thinking. There might be a high probability that a homologue task focused on inventory will not be considering all the cognitive elements that this one considered.	5
Simplicity of the question	Both participants were challenged by this task. For example, when Christie was asked what was the key to deal with the problem she said that it was necessary to read the problem several times: Leerlo muchas veces Laura said that she was overwhelmed by the numbers: So I am overwhelmed by the numbers already However, both participants were able to work with the task	4
Dimensions opened in the pilot by participants	To deal with the task, Laura said that she was going to do the same she did with the sheep. Afterwards, she looked for the value in which there is equilibrium. She is using the homology of system dynamics, knowledge that is enriched by mathematical representations. Laura uses mathematical knowledge to describe what would be happening with the inventory and the production rate. As a function of time? I am looking at x and y axes, that's the why value change as a function of x She also used representations: Zero order, first order, second order, third order, anything beyond that, humans don't really do, so if I look at this image of units per week, that's really the first order as a function of units and then units and inventory is really zero order. Because it's a straight line… so I'm gonna say, because of the straight line business on units per week coming out, one I go to first order, and systems dynamics knowledge I'm gonna have a straight line, but then, knowing that is a dynamic system and there's some second order effects, that I'm having trouble articulating is gotta be second order effects that, coming out of the four weeks lump? Is gonna be some kind of parabolic shape with a smooth transition back to 50.000 level, so that's not really well damped, but it's .. It's gonna be some smooth Here there is another evidence of systems dynamics knowledge I'm going to assume some kind of push or increase in slope to recover the inventory buffer of 50.000 Laura mentioned that it was relevant to talk about inventory as the buffer (stocks), slope in the inventory, production and identified stocks and input and output rates. She also used the word step input when describing the way in which the demand changed over time.	2

Criterion	Assessment of task 4	Score
	Christie tries to see a beyond the limits of the problem asking if the company, after 4 weeks will be stable in time, or if this number of weeks or other elements of the problem or a change will happen. Hay cosas que hay que asumir... Yo asumí que después de las 4 semanas ellos ya se ajustaron, pero es posible que les tomé más semanas, otras 4 semanas otra vez de que tengan el inventario, y eso no está en el problema In this problem, Christie read the task statement several times. She did not understand the graphs and asked why the graph started with week 5. In her way of dealing with the task, she followed the description provided by the problem when thinking about the possible current and future state of the inventory. There is a slight mention of mathematical models and no mention of systems dynamics principles. Calculations of inventory are assuming a linear behavior: , si tengo un inventario inicial de 50 unidades, en la primera semana voy a tener que entregar 11 mil o mejor dicho en la semana 6 voy a tener que entregar 11 mil y voy a producir solo 10 osea que voy a quedar con 49, en la 7 voy a quedar con cuarenta y och… perdón, en la 5 .. en la quinta semana que es cuando me piden eso, quedo con 49, en la sexta quedo con 48, 47, 46; hasta que logro cuadrar mi producción y otra vez logro quedar con 50 mil unidades en inventario… She is aware of time delays though: y como solo tomó 4 semanas hacer el ajuste entonces asumimos que de ahí en adelante logran seguir manteniendo las 50 mil unidades Here she mentioned that there were 4 weeks to adjust but it could be more time, so that assumption should be made. In the graph, she identified the need to draw a relationship between 2 variables. …estamos analizando la relación que existe entre las semanas y las unidades, una fué desde el punto de vista de órdenes y el otro fué desde el punto de vista de inventario. She mentioned that a system is related with the interaction of two or more agents, which show basic knowledge of system's concept. [Los agentes] son los que intervienen en un problema o sistema	
Engineering task/authentic design task	It is not an authentic design task, but it is an analysis engineering task	2.5
Participants show graphical integration - graphics that tell a story about behavior over time.	Yes, both participants used graphs to describe the system's behavior over time.	5

Criterion	Assessment of task 4	Score
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	All elements are present in the tasks performed by the participants.	4

<u>Task 5: The design of a disaster relief scenario</u>: The participants should design a disaster response system, and think about the kind of expertise they need in the team. Points 17.5

Table 3.11 – Assessment of task 5 – The disaster relief scenario

Criterion	Task 5 assessment	Score
Novelty	None of the participants mentioned knowledge of this task.	5
Simplicity of the question	The participants started the task right away. No issues or miss interpretations were reported	5
Dimensions opened in the pilot by participants	Laura saw an “engineering design problem”, and perform a “representational transfer” (using a representation she learned somewhere else) to solve it, focusing mainly on technical considerations. She focused her design scope in making people aware of the emergency. She used the Venn representation she learned from IDEO (a design company) to organize the topics she should consider reaching an innovative solution. According to her, there are three circles that are intersected: usability, technology, and feasibility. Their intersection is that innovative solution. This Venn diagram, uhm.. That's regarding design, so if I'm sitting back, not for a moment, then yes is a design problem. Laura focused her attention on technology first, then in usability and finally in feasibility. Her solution is technology oriented: do I have the technology to answer the question, and then how usable is it for our humans, right? So I forget what the ability word is but I just scribbling it here, technology, technology feasible, vs. cost of the dollar sign. Laura included in her solution: sirens, lock door systems, something similar to what shelter in place is in shooting cases, sending text messages. At the end, she also included “emotional state of preparedness” to be able to “render aid”. She did not mention how to achieve this. She said that it is not in the model she is using to design the response system. The specialties that Laura mentioned in the problem were also technical:	3

Criterion	Task 5 assessment	Score
	like people who are putting together sirens people who install, maintain, operate, turn on [sirens], they are waiting for the phone call or something Christie dealt with this task by identifying first the inputs of the response system, which are outputs of the flooding (which I will interpret as a system that is considered as a black box). First, she thought about what could happen when there is a flooding and how can she deal with those things that could happen: Para mí es más fácil pensar en... Bueno, cuando hay una inundación qué puede pasar, y después hago... Cómo puedo atacar esas cosas que pueden pasar. Her attention related to outputs of the flooding focused on emergency issues and health issues: wounded people, sickness, mosquitos. She also considered that it was relevant to fulfill basic needs like going to the bathroom, having shelter for people. Another way in which Christie dealt with the task was by dividing the problem in three phases: Prevention, what to do when the flooding is happening and what to do later. Vamos a dividir el problema en tres partes, uno, para solucionarlo entonces primero tengo que ver cómo lo puedo prevenir, después cuando ocurre, entonces tengo que ver cómo, cómo lo resuelvo, cuando está ocurriendo, y tercero, eh... Ya cuando sucede todo y todo el mundo está inundado, entonces cómo se actúa después de la inundación. She said that it was relevant to think about the whole cycle, including the time before the emergency, until the time in which everything comes back to normal Tú no puedes mirar una cosa sin mirar la otra porque si no no es una solución completa, tú no puedes decir que solamente ayudo a esta persona a salir de esta inundación y ya me voy de aquí y ya porque es una persona que se quedó sin casa, se quedó sin familia, ehm… y hay que reubicarlos y ver cómo se atienden hasta que estén bien otra vez… entonces por eso [inaudible] como en tres partes. In her design, she iterated, but she focused her attention specifically on prevention hoy por hoy no tiene que ser reactivo, tiene que ser proactivo, y la mejor manera de ser proactivo, es con la prevención, entonces uno tiene que partir con la prevención, entonces uno tiene que partir por la educación a la comunidad para poder ayudar a minimizar el riesgo, la mayoría de los accidentes se pueden minimizar o eliminar si uno logra prevenir When asked about the people on the team and the expertise they would bring, Christie thought about them using the latter approach: who should be there in when preventing, when happening and after the flooding. When preventing, she identified as key people from the community:	

Criterion	Task 5 assessment	Score
	Ok, entonces para prevenir necesitaría gente cercana al… necesitaría gente de la comunidad, una comunidad de vigilancia, de personas que vivan cerca al río Wabash que estén siempre al tanto de cambios en el clima, y de algún... Y de cuando hay lluvias que estén siempre en contacto Christie also talked about the kind of training for these people in the community. The ability she identified was: prevention When preventing, people from the community; when the flooding is happening, health professionals, or those with first aid training. Todos los miembros de la salud (cruz roja, bomberos), … enfermeras doctores…Ahora que lo pienso, es muy improtante que mis personas de la comunidad, también estén en contacto directo con los doctores y enfermeras, incluso que con ellos elaboremos un plan de modo que ellos también sepan algo de primeros auxilios y que ayuden en la comunidad The participants in the pilot showed three ways to deal with the task. Although the number is not high, the amount of critical aspects in which the participant focused on solving the problems is rich. The cross disciplinary perspectives considered by Christie are richer than Laura's, and also her view of sustainability. This task has three ways of dealing with the task, but other components or dimensions make this task complex as a design task.	
Engineering task/ authentic design problem	According to the authors, this is n authentic design task. It is an authentic design problem.	2.5
Participants show graphical integration - integration - graphics that tell a story about behavior over time.	No, none of the participants showed this skill. However, Laura used a graphical representation as her framework.	0
The task elicit need or use of system dynamics in participants (stock and flows, time delays, negative feedback, ability to draw inferences about a dynamic of a system from its structure)	Time delays, ability to draw inferences about a dynamic of a system from its structure, stocks and flow are slightly considered when Christie ask the community to be aware of the level of the river.	1+0.5+ 0.5

3.2.5.5 Pilot 4 – Piloting two variations of task 1, and task 2 using Marton's approach

The final iteration on the pilots was for deciding if the tornado problem was the right problem, and if there was a way to make the manufacturing case more open-ended and inviting to think beyond the boundaries of the problem. For the first task, I piloted the same task with flooding and developed a new one describing a tragedy that should be avoided in an imaginary city in which a new activity in a volcano was putting the little town in danger. I interviewed one professional friend testing flooding, two professional friends using the tornado, and I interview other two friends with the tornado problem. After running these pilots, a long time emergency such as the flooding was not helpful to facilitate to see the variation in long-term thinking. The volcano task made people concentrate in the emergency, and in finding ways to avoid the problem. That made me worry about the possibility of having a task that was not inviting participants to think bigger if they can do it. For the second task, I decided that a way to make you think about how some process is going on is by having unhappy people in the system. Accordingly, I included a conflict between the manufacturing department and the sales department. During the pilot interviews, people involvement worked great. One of my friends, the less experienced one, although aware there was people in the company, did not think about doing anything about it. The others with more expertise mentioned it and proposed actions to minimize their work.

After all these processes, the two tasks selected for data collection in the interview were disaster relief scenario for tornadoes and the manufacturing problem. The next question was which one first. In a personal communication by e-mail, Marton suggested me that the first task should be the more open-ended, so the participants can approach it without pressure, while the second one, should be the one with more structure. The full script is found later is this chapter including the scenarios.

3.3 Data Collection

3.3.1 Institutional Review Board approval to conduct research with human subjects (IRB)

I created a package for the IRB that contained: [1] the survey to capture variation; [2] the interview protocol with the manufacturing case task, which already had the human component incorporated; [3] the volcano task, and the tornado task, advertising that the last two were still under evaluation. Additionally, since some of my participants were from Colombia, I had to translate all my protocols and get approval from an expert in Colombia, that could state that the text of the interview was not offensive or had the potential of enabling me to take advantage of my participants. I contacted the department's head in the systems engineering department who gladly accepted to read the interview and write the letter of approval in English. One iteration with the IRB was necessary before getting the final IRB approval to run the pilots of the two tasks, and finally, start recruiting participants for my research.

3.3.2 Recruitment

The recruitment of participants was slightly different for students and professionals because undergraduate students were invited randomly, while professionals were invited by purpose sampling. Additionally, the order of the procedures was also different.

3.3.2.1 Undergraduate Students

I posted pamphlets in different engineering buildings and libraries at Purdue University on bulletine boards. Additionally, I asked the office of the registrar mailing service to send an e-mail inviting them to participate in the study. The e-mail described the study and the time student would need to invest in participating fully in the project. It also had a link, in which the student click in case she decided to participate. The link took the participants to the online survey that was developed to capture their variation. The procedure was very promising at the beginning because I just needed ten students, and 33 started the survey. Only 19 of those completed the survey. With the information collected in the survey, and to keep a rigorous process, I organized these 19 per academic year: eight were in their first year, one was a sophomore, 6 were in their third year, and 3 were seniors. The purpose was to be sure I had at least two undergraduate students per academic year. I also assigned scores to each experience students have based on how close was that experience they narrated to a problem in a complex system. Weights to the experiences were also added, since it was not the same, regarding the experience addressing socio-technical systems, to have a co-op experience than having experience working in a restaurant as a cashier. Data were also normalized to make them comparable. With this data, I created a graphical representation of student's experience to be able to compare it with the experience of another student, and in that way, ensure variation in the experiences of the sample. In Figure 2.1you will find a sample of the graphical representation of experiences of four undergraduate students.

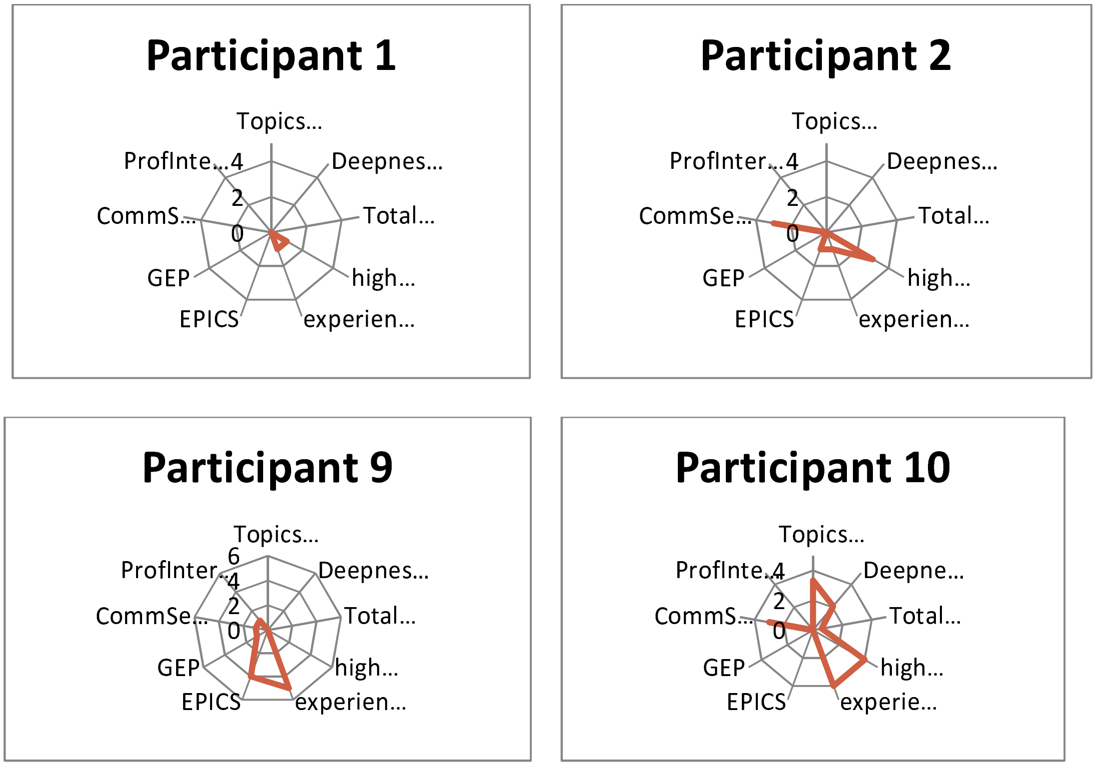


Figure 3.3 - Graphical representation of some student's experiences

After conducting this process, ten undergraduate students were invited to the second phase of the project, the interview. I invited two first years (who accepted), the sophomore (who accepted), three third year (who accepted), and the three seniors (none accepted). After this experience, the deep analysis of the experiences was dropped, and I focused on recruiting participants who were senior. Finally, two seniors were recruited successfully, and another junior to complete ten students that were my goal for capturing the possible dimensions of variation that undergraduate engineering students opened when they address complex socio-technical systems. Still, the students are very different regarding their experiences. You can observe this variation in Table 3.12.

Table 3.12 - Map of undergraduate students' experiences variation

Participant Number	**Item**	**5**	**16**	**6**	**2**	**3**	**7**	**12**	**21**	**19**	**22**
Academic Year	Undergrad - first year	x	x								
	Undergrad - Sophomore year			x							
	Undergrad - Junior				x	x	x	x	x		
	Undergrad – Senior									x	x
Size of the city they are coming from	US-small town: population <100 thousand people					x			x		
	US-Middle size city: population < 500 thousand people			x			x				x
	US-Big City: Population > 500 thousand people							x			
	China – Mainland									x	
	East Europe	x									
	US-Indiana (town: undetermined)		x								
Professional discipline	Acoustical Engineering						U				x
	Aeronautical and Astronautical Engineering										U
	Biomedical Engineering			U							
	Chemical Engineering									U	
	Electrical Engineering		U								
	Engineering Management								U		
	Industrial Engineering	U				U					
	Mechanical Engineering				U			U			

	Years of high school/ undergrad/ Grad outside of US	H						H			
Gender	Male		x	x			x			x	x
	Female	x			x	x		x	x		
Nationality	United States		x	x	x	x	x	x	x		x
	Europe	x									
	South America										
	Africa										
	China									x	
Race / Etnicity	White	x	x	x		x	x	x	x		x
	African-American										
	African										
	Latino				x						
	Asian									x	
ST-Instruction: Undergraduates	High: 4<=x<5				x			x		x	
	Medium: 3<x<4										
	Low: x<3					x	x		x		
	0 or not reported	x	x	x							x

Regarding their experiences in EPICS, Global engineering programs, community service, professional internships or co-ops, and jobs on campus and outside campus, there is also variation in their experiences, as can be seen in Table 3.12.

Table 3.13 – Students'experiences in EPICS, GEP, Community Service, Internships and co-ops

		Undergraduates									
		5	**16**	**6**	**2**	**3**	**7**	**12**	**21**	**19**	**22**
EPICS	High			X							
	Medium										
	Low	x							x		x
Global Engineering Program	Low			X					x		
Community Service	High		x	X							
	Medium								x		x

		Undergraduates									
		5	16	6	2	3	7	12	21	19	22
	Low	x		X	x						
Professional internships	High										
	Medium							x			
	Low			X	x	x					
Jobs related to field	High										x
	Medium					x					
	Low			X	x			x	x	x	
Jobs Not Related with field	High										
	Medium										
	Low				x				x	x	x
Jobs Not Related with field outside campus	High		x			x					
	Medium										
	Low			X					x		x
experiences with Complex systems	High			X		x	x	x	x		x
	Medium									x	
	Low	x	x		x						

3.3.2.2 Professionals

Purposeful sampling was the way in which professionals were invited to participate. As expressed above, in the section for validity and trasnferability, I used the criteria of years of experience, gender, race, field, and availability. It was difficult to find African-Americans willing to participate in the study (I sent invitations to different engineering African American professional societies, and friends also spread out the message), and it was also difficult to recruit participants in the range of 5-10 years of experience. In this case, the procedure was slightly different. First, they were interviewed, later they were asked to complete the survey to capture their variation, which was used to confirm that the pool of professionals invited to the study had the variation required to ensure validity and transferability. The variation in the professionals can be seen in Table 3.14

Table 3.14 - Map of professional participant's variation

		Consecutive assigned to professionals															
		4	**9**	**18**	**23**	**24**	**25**	**26**	**10**	**11**	**20**	**1**	**8**	**13**	**14**	**17**	**15**
Professional experience	1 year	x															
	1-5 years		x	x													
	5-10 years				X	X	x	x									
	10-20 years								x	x	x						
	More than 20 years											x	x	x	x	x	x
Gender	Male				X		x			x		x	x	x	x		
	Female	x	x	x		x		x	x		x					x	x
Certifications	PMI										x						
Nationality	United States			x	X			x	x					x	x	x	x
	Europe																
	South America	x				x	x			x	x		x				
	Africa											x					
	China		x														
Race / Etnicity	White			x					x				x	x	x	x	x
	African-American				X												
	African											x					
	Latino	x				x	x			x	x		x				
	Asian		x														

3.3.3 The interview

The interview had the following sections: [0] Informed consent [1] a rapport section, [2] two warming up problems borrowed from Marton that allowed the participant to practice think aloud and helped me to switch to interviewer mode. [3] Disaster relief scenario for tornadoes task, asking for issues and team members. Here the participant was asked to think aloud while addressing the task, and at the same time received probed questions from the interviewer. [4] Interview about why the participant did what she did. [5] Manufacturing case including non-happy workers in the company, and conflict between units. [6] Interview about why the participant did what she did. [7] Participant is asked about one, two or three similar problems to the one she addressed in task 1, and after she had presented the problem, she is asked about the reasons why these were similar. [8] Participant is asked about one, two, or three similar problems to problem 2, and after that, she is asked to explain why these problems were similar. [9] Participant is asked for similarities and differences between task 1 and task 2. [10] Participants are asked how they would teach how to address these problems in the same way she addresses them. [11] Closing the interview

First, I am assuming that any participant who accepted to participate in a performance task, wanted to do well. Second, the interview has the goal of facilitating the participant to open all the dimensions of variation she can open, or in other words, to ask her to open her maximum level of awareness to consider the critical aspects of a problem in a complex system. That is why we iterate on the first problem after considering the second one. I believe there could be a chance that the participant opens a dimension on the second task, and when she iterates on the first one, she makes the note. Likewise, we iterate on task 2, after coming back to task 1. After asking for similar problems, they are asked to compare the tasks. This iteration was conceived as a reinforcement of the previous step. Additionally, the idea of asking for similar problems was a way of using Dr. Linder's advice (a phenomenographer from Uppsala University who accepted to meet me by skype once). He suggested asking the participant for different ways in which she would explain what the problem was, that would allow me to find more about her way of seeing.

I must acknowledge that not all the interviews ran in the same way. In the Skype interviews, it was more difficult to ask probe questions sometimes because of the quality of the signal, or because the signal just drops. Participants 1 and 4 were not asked about the team in problem 1, although they opened that dimension naturally. In the interview 8, the participant did not receive the task in advance, and I had to read it aloud. Additionally, the conversation was not fluid because there were moments in which I barely understood what the participant was saying. The four most difficult ones to transcribe were those with participants 3, 8, 17, and 23. However, I believe that the data collected from these participants is valid, because my interest in in the dimensions of variation they opened during their interview, and not in their performance. In table Table 3.15 you can find the full interview.

Table 3.15 – Full Interview used for data collection

Good morning/ afternoon. Thank you for taking the time for this interview. To ensure that my starting point of the conversation is the same for all the participants, I will be reading part of this interview. Accordingly, it may not sound like a natural conversation, but it is a necessary caution that I want to make as researcher to avoid noise produce by my mood while doing the interview [0] Informed consent [1] Rapport Section a. In this interview, I will be posing two different scenarios in which I will ask you to tell me what you would do to respond to the case I am giving to you. Your job is to approach them you might approach a similar scenario in your everyday life. b. While approaching each task, you will be asked questions about the meaning of what you are doing. If you feel uncomfortable about any of the questions or do not wish to answer any question, feel free to tell me, I will move on to the next question. c. I am not looking for any particular answer. I just want to know what are you seeing, and the issues you pay attention to, while addressing the task Before we start, please tell me some of your backgrounds: a. Where are you from?

b. What is your engineering discipline?
c. Do you belong to any professional organization (INCOSE, ELAPDIS, ISSS, etc)?
d. How much time of experience do you have?
e. Are you a fellow?
f. Do you have any certification?
g. Do you hear in your environment words or expressions related to systems?

[3] Warming up

Thank you, let's start. In this interview, I will pose some scenarios or problems, and I will ask you to think aloud while dealing with them. It is extremely valuable for me to hear your thought processes, and every detail is relevant. Remember also that I will not judge any of your answers; there are no right or wrong answers.

I will also provide pen and paper in case you may need it. (In case the interview is by skype or google hangout I would say: "Please, to get ready, have some paper and a pen at hand to use them in case you needed when dealing with the problems I'll give you".) Additionally, you are free to use any tool you think you need to address the problem.

Let's practice the think aloud process. Remember to say aloud everything you are thinking, even if it seems trivial. Could you please tell me "How can two numbers make 12" ?

Now consider the following case, One shop in a town sells hot dogs. They are sold at $5 and people from town usually buy them. Suppose that you are the new owner of the shop. What price would you set for a hot dog? Would you set the current price or a different price? What would you consider when you set the price?

[4] Disaster relief scenario

Recent natural disasters (e.g. Tsunamis, earthquakes, tornados, fires, and floods) were a hot topic at the International Conference On Predicting And Responding To National Disasters last month. The conference brought in people with diverse backgrounds from around the world, particularly those who live or work in "disaster plagued" areas such Florida and Singapore. At the end of the conference, you were asked to bring together a team that would focus on developing new ideas for a "disaster response system" for tornadoes in Tippecanoe county, Indiana.

- What issues do you think are essential to consider and who would be on your team? Please use the back of this page if you need more space.

[4] Interview asking for the meaning of what the participant did in task 1.

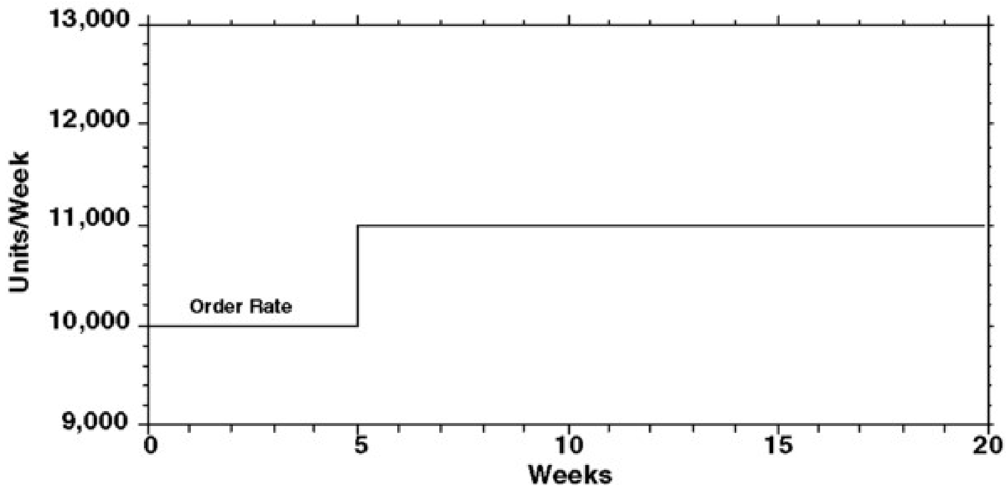
[5] Manufacturing case

I am going to pose a problem related to a manufacturing firm. The firm maintains an inventory of a finished product. The firm uses this inventory to fill customer orders as they come in. Historically, orders have averaged 10,000 units per week. Because customer orders are quite variable, the firm strives to maintain an inventory of 50,000 units to provide excellent customer service (that is to be able to fill essentially 100% of every order), and they adjust production schedules to close any gap between the desired and actual level. Although the firm has ample capacity to handle variations in demand, it always takes 4 weeks to the company to adjust the production schedule. Manufacturing workers are sometimes not completely happy about these changes in the production schedule and have issues with people from the sales department. Yet, the company keeps their manufacturing goals and reaches them.

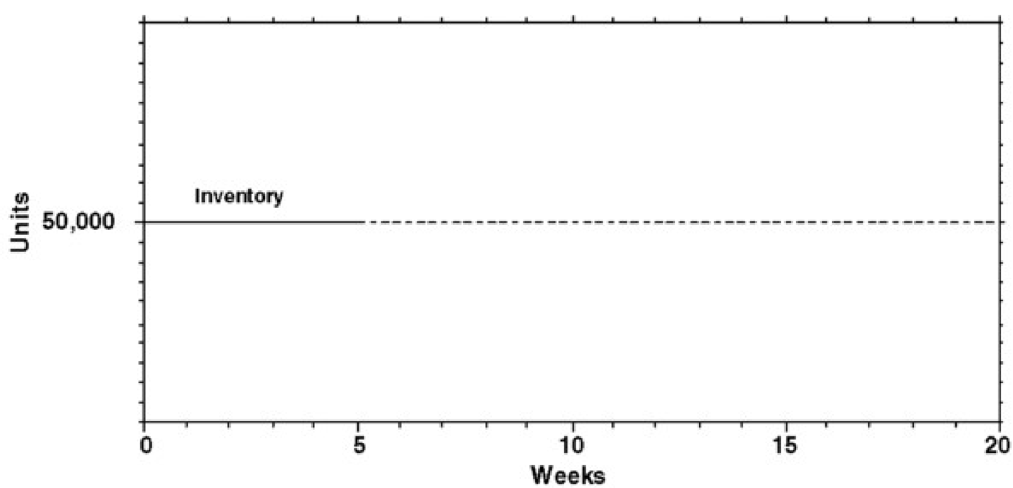
Now imagine that the order rate for the firm's products suddenly and unexpectedly rises by 10%, and remains at the new, higher rate indefinitely, as shown below in the graph. Before the change in demand, production was equal to orders at 10,000 units/week, and inventory was equal to the desired level of 50,000 units.

Sketch the likely path of production and inventory below on the graphs. Provide an appropriate scale for the graph of inventory.

**PRODUCTION OF FINALIZED PRODUCT
IN THE MANUFACTURING COMPANY FOR 20 WEEKS**



INVENTORY OF FINALIZED PRODUCT IN THE MANUFACTURING COMPANY



[6] Interview asking for the meaning of what the participant did in task 2.
[7] Can you think in one, two or three problems similar to problem 1? Why are they similar to problem 1?
[8] Can you think in one, two or three problems similar to problem 2? Why are they similar to problem 2?
[9] Based on what you did, how would you contrast and compare these two problems? Is there any similarity in the way in which you address them?
[10] If you want to teach other people how to address these kinds of problems, what would be those key elements they should consider and pay attention to do it successfully?
[11] Thank you very much for your time, do you have any questions for me?

3.4 Data analysis

Audio transcripts were transcribed verbatim. I transcribed nine interviews 26%, and the remaining were transcribed by a transcription service. After receiving the transcripts, I listened to the audio records and read the transcripts simultaneously for accuracy checking. I created a code for the transcriptions composed of five subcodes: [1] a consecutive number, in regards of the order in which the interview was done. [2] a consecutive for the kind of participant, 'P' for professionals, 'US' for undergrad students. [3] If it was a professional, this subcode stands for the kind of professional I interviewed: 'EF' for engineering faculty, 'IP' for industry professional, 'GS' for grad student. On the contrary, if the participant was a student, this subcode was defined in regards of the academic year in which the student was going from '01' for first year students to '04' for senior students. [4] This subcode shows if the interview was hold in English ('En'), or in Spanish ('Sp'). [5] Finally, this subcode showed the participant's gender: 'F' for female, and 'M' for male. For example, the code 01-P01-IP01-En-M stands for a transcript of the first participant that was interviewed, who was also the first professional in my sample. The interview was in english and the participant was a male.

3.4.1 Finding the way to seek for dimensions of variation

I must recognize that I was confused at the beginning of understanding what the unit of analysis was, and in how to do phenomenography using Marton's idea of seeking for quotes. According to Marton, the unit of analysis is a "way of dealing with the task". The examples I found in the literature were about a single task directly related with the object of learning under study. In my case, I had two tasks, and the object of learning was supposed to be “extracted” from the two. This idea looked good on paper, but it was challenging for me: was not a participant’s way of dealing with the task found in the whole transcript? Or at least in the whole transcript for a task? How can you observe the full meaning of a participant’s way of dealing with the task from quotes? Those were the kind of questions that came to my mind at that time. I asked a phenomenographer from Honk Kong, Dr. Pang, for advice. He told me that the advice he gives to students doing phenomenography is to read the transcripts several times looking for meanings and that with the time, the meanings would emerge. Still, it was confusing for me to understand this idea.

In my third reading, keeping in my mind Marton’s idea of the experience as a “way of seeing”, I kept in my mind that I was seeking to understand “the particular way in which the participant saw the problem while she was addressing the task”. I decided to focus only on the tasks individually. It also made sense to me to use Nvivo to support data analys. While I was reading, I started to select quotes that described the topics the participant was identifying. Later, I did something similar with task 2. And in my mind was the idea that these topics would allow me to understand what was the participant seeing and that common topics would give me as a result, the dimensions of variation I was seeking. When I presented preliminary results on this to my advisors, they raised a flag, helping me to realize that I was doing content analysis instead of phenomenography. Doing the detailed analysis helped me to have a deeper knowledge of the transcripts. Dr. Oakes suggested me to take the whole transcript approach for data analysis since the way of dealing with the task was inmersed on each participants’ practice. Accordingly, he suggested me to classify participant's performance without being too detailed in the reasons why I felt one had a higher performance than the other. I did this iteration and classified them. This classification was useful for me later. Such iteration looked the right way for my advisors but not to me. I asked Marton how is it that I was supposed to find meaning in a quote, and his answer helped me to clarify my understanding of the method. His answer was that it was not possible to find meaning in quotes from just one transcript, but in comparing quotes that were talking about a similar idea from different transcripts. He also told me that what I was not looking for differences in people performance, but for aspects of the object of learning, which later I understood as the dimensions of variation I needed to identify. Later I found that he explained this idea on page 85 of his 2014 book, and I missed that information, even though I read it several times because I was not able to understand it (I guess I opened a dimension of variation that increased my level of awareness). Also, I found a quote from Marton and Booth (1997) who said that different aspects of the object of learning might be studied separatedly. Since my two tasks were maybe tackling different aspects of the object of learning, it made sense to me now to study them separatedly first.

3.4.2 Seeking dimensions of variation – The 17 iterations.

You cannot recognize a dimension of variation immediately in the data, what you see are features or values of that dimension across different transcripts. I realized of this in my first iteration knowing better what I should seek in the data. Since task 1 brought me into a lot of confusion because its nature pulled me out to look for content, instead of dimensions of variation, I started this new phase of the data analysis with task 2. Borrowing the same technique used by cope (2000), I kept wondering "what this quote is telling me about the way the participant deals with the problem?" Hence, I finally understood why the quote is extracted still considering the context from which it was taken. I was not focused on right or wrong, but in quotes that were giving me some idea of variation.

For this iteration, I chose eight transcripts from participants in different ranges of performance (I used the classification from a previous iteration). These transcripts were from these participants: 1, 2, 4, 6, 10, 17, 24 and 25. This time, for data analysis, I used mind manager to select the quotes. Since I have already read the transcripts several times, I started the selection of quotes from individual participants, based on my understanding of all the participants. Once I had the quotes from all the different participants included in this sub study, I printed them on paper and read them again. At that moment, I started to experience the variation in the data and understood the idea of features that together form a dimension of variation, which means that I found that participants were talking about an aspect with different levels of "knowledge." Accordingly I organized them in piles, looking for those that expressed something similar. Later I picked them up from the table, and I read them again to verify if the quote made sense in the group I was locating it and represented one of the values within that dimension. If it does not, I looked if it fits in another category, or if I just should return it to a general unclassified pool. Studying if they should be somewhere else also allowed me to enrich the description given for the dimension composed of a set of quotes.

3.4.2.1 Iteration 03

In the first iteration using this approach, but the third globally considered analyzing the data, I proposed the following dimensions of variations that can be found in Table 3.16 (each supported by two or more quotes):

Table 3.16 – DoV proposed in Iteration 03

- To make sense of the problem and go about it, a previously learned model is used
- Use of scenarios
- Looking for a bigger picture of the problem
- Looking for a bigger picture of the problem, going beyond the limits of the problem
- Planning considering bigger picture (demand or order rate)
- Looking for a bigger picture of the problem, going beyond the limits of the problem, this time including other teams to address the problem
- Planning considering past, delays
- Planning considering past, delays, and details (keeping in mind the big picture, but also considering details)
- Considering how everything interacts to reach the goal of the organization
- having a goal in mind
- Perceiving interaction, but not knowing how to understand it or represent it

You may see that there might be dimensions that were very close to each other, for example, all of those starting by planning. That result was confusing for me because I had identified too many values that were close to each other. Later, in iteration 06, I realized that these close dimensions of variation were not dimensions but features within that dimension of planning.

3.4.2.2 Iteration 04.

Since I was not happy with the outcome obtained, I started over. I increased the number of transcripts to 16, and applied a similar technique in data analysis, with an increased awareness of how a dimension of variation could look like in the data when you compare it with others. In this iteration the following dimensions of variation presented in Table 3.17were identified:

Table 3.17 - DoV proposed in iteration 04

• Considering Interaction among components in the system • math models • models (system's engineering process, lean manufacturing, systems dynamics behaviors) • System goals (e.g. company's goals) • Relationship with other systems in the Environment (e.g. clients). One direction or two directions? Other systems identified that directly or indirectly interact with my system and could affect my ability to create an output • Inside the box (e.g. workers, identifying sub processess) - details • Decision making • Reflection • Communication

As you can see, this time, was easier to perceive what could be a critical aspect necessary to deal with the task, and how different participants show variation within that dimension. It also helped me a personal comunication by e-mail with Marton, who showed me an example using my data. I asked him about delays, and he said that, if it was relevant for students to learn about them, and if I perceived variation in its understanding, that would be a critical aspect or a critical dimension of variation (DoV).

3.4.2.3 Iteration 05.

Here two dimensions were scrutinized for a better understanding. I had models and mathematical models in separated categories, and I wondered: was there any difference between saying that the person was opening math models DoV or that a person is opening the DoV models. My rationale was:

> The key idea is that you need to use models to deal better with the problem. Accordingly, math models and models, in general, could be in the same dimension of variation, that in the future values of the dimension can be explored as possible dimensions of variation. (My journal notes. March 29, 2016).

The categories math models and models were fusioned in this iteration, and the values I had on mathematical models, are now subvalues of models.
The reflection also considered the DoV delays:

> What about delays? Currently, delays are a value within the interaction between variables. However, understanding the impact of delays between the moment an action is performed and the moment in which you can see a response is not trivial. Accordingly, understanding delays should be a dimension of variation itself. (My Journal Notes. March 29, 2016).

3.4.2.4 Iteration 06.

After accepting a suggestion from Dr. Oakes, I came back to my first iteration and compared my current DoVs with the ones I identified there and later discarded. It was surprising to me to find that what I did in that 3rd iteration was on the right path. See Table 3.18.

Table 3.18 - DoVs from iteration 03 vs. DoVs from iteration 05 – April 3rd

Dimensions identified in iteration 03	**Dimensions identified in iteration 05 that matches those in iteration 02**
To make sense of the problem and go about it, a previously learned model is used	Using models
Use of scenarios	
Looking for a bigger picture of the problem	Information gathering
Planning considering bigger picture (demand or order rate)	
Looking for a bigger picture of the problem, going beyond the limits of the problem, this time including other teams to address the problem	Relationship with other systems in the Environment (e.g. clients). One direction or two directions? Other systems identified that directly or indirectly interact with my system and could affect my ability to create an output
Planning considering past, delays, and details (keeping in mind the big picture, but also considering details)	
Considering how everything interacts to reach the goal of the organization	Considering Interaction among components in the system
Having a goal in mind…	System goals (e.g. company's goals)
Perceiving interaction, but not knowing how to understand it or represent it	Considering Interaction among components in the system. Value: One component at a time.
Strategy to reach goals	

3.4.2.5 Iteration 07.

I decided to study now the variation in task 01.With this task, as I stated above, it was challenging not to be thinking in content and keep looking for the meaning of considering certain issues. Some preliminary notes from my research journal that helped me to think about the dimensions of variation are shared in Table 3.19. This time, I studied the first 17 participants in my list without considering performance because they covered the variation in experiences from professional experience: 10 professionals: 3 Engineering Faculty, 6 industry professionals, 1 Graduate Student. 6 undergrads: first, second and third year.

Table 3.19 - - Journal notes when studying task 01 – April 03, 2016

If constraints are overlooked, does it mean that it is a dimension of variation that needs to be opened? Types of gathering info (are these features?) Gathering information to identify variables…. Gathering information from the user about what is wanted Gathering information to determine what the real problem is It is different to produce an outcome than to produce an outcome that is liked by the customer. Some participants said they need the customers to buy into the system or the solution… Some people developed the solution thinking on what is the best… for some others, it was really important that the community buys into the solution… requirements were developed with the community and keeping in mind the regulations… Solutions that can be applied to other problems… generalization More emphasis on idea generation Be aware of regulations when proposing ideas… To organize what I painted in the whiteboard, that was based on the quotes I will think about those dimensions of variation that participants opened when they were thinking about addressing task 1… what are those features or values participants opened up

In this iteration I identified 13 DoV that you can see in Table 3.20.

Table 3.20 – DoV found in Iteration 07

Effort in problem scoping
Effort in idea generation before thinking in a solution
Relationship system – user
Taking advantage of interdisciplinary team (relationship with team)
Managing the interdisciplinary team
Consider leadership
Design considering different possible alternatives
Communication
Testing/validation (how well is doing?)/iteration/ learning
Defined strategies for idea generation/idea reduction/idea selection
Models to understand reality
Models to intervene
Time as a variable you can play with

Effort in problem scoping
Effort in idea generation before thinking in a solution
Relationship system – user
Taking advantage of interdisciplinary team (relationship with team)
Managing the interdisciplinary team
Consider leadership
Design considering different possible alternatives
Communication
Testing/validation (how well is doing?)/iteration/ learning
Defined strategies for idea generation/idea reduction/idea selection
Models to understand reality
Models to intervene
Time as a variable you can play with

It is relevant to mention that for each dimension of variation I found features that were more advanced than others, that is why I was allowed to say it was a dimension of variation.

3.4.2.6 Iteration 08.

Here, I studied the DoVs from task 1 plus the Dovs from tasks 2. The number of global DoV was increased by a big number. I found several possible dimensions of variation after getting deeper into the data. 24 dimensions of variation were found (See Table 3.21). It made me stop and reflect about what a critical dimension of variation was. Coming back to Marton's book (2014), critical aspects of the object of learning are those aspects she needs to learn to deal with the problem in a more powerful way. In this quote, I show a better understanding of a DoV. In this iteration I also decided to put the name variation in the name, trying to be consciously sure that there is variation in the dimension. Maybe later, once I am sure of the variation, I would erase the variation word in the dimension's name, to call it a critical aspect of the object of learning.

> So, I am not looking for content, not looking for act + content, but looking for critical aspects... What are those things that vary? The person needs to learn about how that aspect varies….
>
> That is why the distribution of effort in a design task is a critical aspect … it is variable, and if you can see how it varies from novices to experts, that makes the learner make the aspect their own! My journal notes. (April 7th. 2016).

Table 3.21 - DoV found in Iteration 08

- variation in Effort in problem scoping … or Variation in ways of identifying the problem
  variation in ways to deal with the lack of information
- variation in the ways of understanding the goal of the system
- variation on effort on diverging (idea generation) before thinking about a solution
- Variation in ways of engaging in metacognition
- variation in ways to Communicate
- variation in the ways in which the system interacts with the user
- Variation in the ways of doing teamwork (e.g. relationship with team)
- variation of ways in which leadership is considered
- Variations in the understanding of time
- Variation in perception of time delays
- variation in ways to test or validate if the system is reaching its goal, and in ways to improve ..
  Testing/validation (how well is doing?)/iteration/ learning
- Design considering different possible alternatives
- variation in ways to study how things interact with them
- Variation in ways to be prepared and adapt to changes in the environment. Related to studying how components interact. Included in iteration 09.
- Variation in ways of perception of the role of stakeholders
- Variation in ways of making decisions
- Variation in the ways to perceive the owner of the task

• Variation in the ways of seeing the socio-technical relationship: inside the organization or even including other systems around. (Included in iteration 09) • Variation in the way the system is perceived. This dimension is included in setting the boundaires of the system. • Managing the interdisciplinary team (included in relationship with team) • Defined strategies for idea generation/idea reduction/idea selection

In

Table 3.22 you will find the reflection that leads to the reduction and definition of a new set of DoVs for task 1. The entries here showed random thoughts that came to my mind while I was reflecting on the data and the categories thinking what could have been valuable for a leaner.

Table 3.22 - Reflections on iteration 08 – April 7th, 2016

What do they need to learn? Quotes cannot give me full categories; categories could be composed of several quotes.... Makes me think that t I am right For example, they need to learn that it is better to work with experts from different disciplines in a participative way, rather than in isolation They need to learn that the success of the systems solution is because it is addressing the right need, and to identify the right need, people should have been involved in the definition of the need, and in the solutions That design should always meet requirements, functional, and nonfunctional They need to learn that is key spending time, or putting great effort on problem definition They need to learn to go big when identifying all the different supra systems, subsystems, and partner systems that interact with my system They need to learn that the problem should be observed from all different possible perspectives, so you don't miss in your solution to address the need of any of your stakeholders To study interaction at the same time... Maybe here models are useful... If I think about the environment, disconnected from people does not make sense... That is not a problem... Is it?...

What else is critical? Team? To diverge, converge, make decisions and continue... Because solution is not final and it will improve after testing and validation Effects are not always seen immediately and mechanisms to see these effects are needed You need ways to predict the future Knowing about practices... Not items... So what is the practice regarding including politicians? Going from particular to general, and from general to particular Being engaged in metacognitive processes Understand details to understand the big picture... Try to see wholes... Focusing on outcome, but understand that the system should be flexible and should adapt to changes in environment There are direct and indirect stakeholders, and effort is needed to identify them..... Also, that public policy should be followed

3.4.2.7 Iteration 09.

I considered in this iteration the two tasks. As it was shown, I was still struggling with having too many DoV, and I kept wondering:

> What are those that are critical specifically for the object of learning which is dealing with problems in complex systems? … [later I said] What am I able to see in those who perform better than the others in general? Which is similar to Marton's question, what makes some people better than others at dealing with a problem, or with these two problems. (My Journal, April 9, 2016).

In this quote, you can see that I put my instructor's hat "on." It makes sense now to have different descriptions of the object of learning, as Marton do have three: The intended (planned by instructor), the enacted (offered by instructor) and the lived object of learning (discerned by the learner). Here we are hoping to find all the aspects of the intended object of learning, using all the different lived objects of learning offered by participants.

Accordingly, with that idea of different lived objects of learning, it makes me understand another methodological step. The quotes are studied in isolation from the context, but also later in the context in which they were formulated.

According to my new understanding of the methodology, which has been stated several times by Marton in different articles, but was not clicked in my mind until recently, I read the quotes from different participants and compared them with other participants. For example, I took participants P1-expert, P2-novice, P11-Expert, and P4-novice. I noticed some differences in aspects for example P1 was able to talk about, that for example P2 or P4 did not consider and made their answers less powerful. A new round considering aspects relevant to be learned to address complex socio-technical systems were selected. 13 DoVs were selected or redefined for iteration 09, as you can see in Table 3.23

Table 3.23 - DoVs proposed in Iteration 09

From task 1: **Variation in problem scoping:** Learners will be going from thinking that the problem is already defined, to talk to the task owner, or to talk to the users about defining the problem.

From task 1 and task 2 (in iterations 04, 05 and 06, focused on task 2, that was called relationships with other systems in the environment and was in the same group as the relationship with the client. In this iteration idea of seeking for relationships with other systems is in this category, while the relationship with the customer is a different one): **Variation in setting the boundaries of the system**. This is related to the effort in identifying what could be inside of the system, and what would be outside, but interacts with the system directly or indirectly. This approach is usually used to define scope, and it is related to problem scoping, but it is in a different category because it is related to the idea of Trying to see a bigger picture, diverge and going big. The idea generation was mainly regarding answering "what else should be included", or in what else would interact.
From task 1 and task 2: **Variation in ways of engaging in metacognition**. After reading about metacognitive processes (Bransford et al., 2000), and Pellegrino (Pellegrino, 2006), I came back to the idea that some of the participants are engaged in metacognitive processes when they are dealing with the task.
From task 1 and task 2: **Variation regarding the relevance of effective communication.** From t1, quotes that mentioned that it was necessary that the communication inside the system is effective, and that the communication to external stakeholders should also be tailored. For example, they mentioned that logistics should work well, the communication among all the people attending the emergence. Also the communication with different levels of command. Also in communicating the design within teams while designing the solution, or in communicating with the owner of the task. In task 2, communication between dependences to deal with conflicts, for example, communicate with people from the sales department because the system cannot respond immediately but it takes four weeks to respond.
From T1 and t2: In iterations 04, 05 and 06, I was considering a relationship with users as the same as relationships with other systems. However, since learning about powerful ways to relate with the customer is critical for success in addressing this kind of problems, the relationship with the user will be an independent category. **Variation in the understanding of how the system interacts with the user.** Here is the consideration of users that need to follow the system showing a hierarchical relationship in which the system is imposed (and what is needed is that the system is easy to use, and must be followed), or the user as participating in the design of the solution. In task 2, the company has the goal of satisfying customer demand, but also to keep 50 thousand units of inventory. Participants may change the goals of keeping that inventory base on the change in demand, or may be trying to keep the same goal, or may be changing the goal based on "good practices" of inventory. The first and the latter, show that the user needs shape the goal of the system while keeping the same level shows that the system's goal does not depend on the customer.
t1 & t2: **Variation in working in an interdisciplinary team:** cooperative, collaborative, consultative.
From T1 and t2: Variation in **Long-term thinking:** from not being aware, to be aware, to represent it, to use simulations or other tools to see the future.
From task 1 and task 2: **Variation in efforts to validate.** In some cases, the validation was focused on the output, but in some others, the validation was a process that was done the whole time, from problem definition to the end.
From t1, t2. Since they do not need to learn the models, but how to use them: **variation in the ability to abstract the relevant from reality to a conceptual model, and in using the model to apply to other situations.**
From t1 and t2: **Variation in ways to study how components identified interact. V**isible especially in task 2 when they were either studying the behavior of isolated components contributing to reaching the goal or when the quote shows studying all the components at the same time. Visible in task 1 when they were considering scenarios to be able to develop different responses according to the level of the tragedy.
New in iter 09: **Dimension of factual knowledge (similar to paying attention to details. Answering: why some people were able to think about details while others were not?)**. For task 1 We can see here that there are quotes that reflect knowledge in disaster recovery. In here you can see that there are proposals on how the system should be. Some others have the experiential knowledge, and some others have no experience. In Task 2, there are quotes that show knowledge regarding having a big inventory as a bad idea. These suggestions cannot be considered if you don't know about the topic. These quotes also show that in these cases you can go to the details (see P8 and P15 for task 2, and P11, P17, P1). Other examples: For example, in Task 1,

participants talk about individuals getting prepared or trainted, teams also prepared. For task 2 they talked about timing between steps in the process, but also about making the workers happy.
From task 2 and task 1: Variation in decision making. **Variation in the information they need to make decisions**, or in what they do to make decision when there is no information

3.4.2.8 Iteration 10.

I did this iteration after sharing the results with Dr. Oakes, one of my advisors. In the meeting, the concern was about the category making decisions, a concern I also had because although everyone makes decisions, that doesn't seem to be an isolated dimension of variation, but a feature within one or more dimensions. For example, people use models to gather information to make decisions. In this iteration just the name of the variation in setting the boundaries of the system were changed as you can see in Table 3.24:

Table 3.24 – Names changed in iteration 10

Name in iteration 09	**Name in iteration 10**	**Explanation of the change**
Variation in setting the boundaries of the system	Variation in seeing the complexity.	This category is about participants identifying the components that interact. And the systems that interact with my system. Although setting the boundaries helped regarding thinking what was included in the system, still the name was not covering for example identification of components in different levels of the system.

3.4.2.9 Iteration 11.

In this iteration, the DoVs were revised again trying to find names that better described the variation found within the dimensions. Also, variation in some dimensions was arranged regarding the higher level of awareness within the dimension. You can find the details on this iteration in Table 3.25

Table 3.25 - Iteration 11 - Log of changes in the DoV

Name in iteration 10	**Name in iteration 11**	**Explanation of the change**
Problem scoping	Variation in strategies to perform problem scoping	The variation found within this dimension ranges from learners doing problem definition by themselves to participants doing problem definition involving stakeholders, experts, task owner and data from the current system in place and other data.
Variation in seeing the complexity	Variation in the layer levels in which the different interacting components considered are	This describes that the participants are seeing components ranging from components at the same level, to components that contain the system: [1] same system level, [2] awareness of sub-systems as contributors to the system (e.g. workers in task 2, or operators of the system in task 1, [3] Identifying also other systems that are at the same level and could help or compete with the system (e.g. companies whose workers are hired when there is a higher demand in task 2, or seek agreements with organizations of volunteers who can help if a tornado hits. [4] Systems that are above, also called supra-systems (e.g. in task 1, thinking at the level of people, city, county, and state). Studying the interaction is part of the dimension of variation regarding models.
Variation in ways of engaging in metacognition	Variation in ways of engaging in metacognition	Here the name did not change, but in a meeting with my advisors, Dr. Cardella and Dr. Oakes, I told them that it was difficult for me not to see metacognition in the participants. I also told them there was some variation, but I did not think I should focus on studying that variation deeper because it was not within the scope of the project. We thought that maybe is a threshold that is needed to be able to open more dimensions of variation, but this should be validated later.
Variation in the understanding of how the system interacts with the Stakeholders (in how the stakeholders are taken into account).	Variation in awareness of stakeholders	Here you will find variation regarding the kind of stakeholders the participants considered relevant, from not considering any stakeholder, to have an awareness of other systems that compete with them. This dimension might be related to the dimension of variation regarding the level in which the different components identified interact. No stakeholder, only the system, stake holders affected directly and in the short term, internal users are also considered. Then, there is awareness of regulation entities, and awareness of other systems that could help my system, or compete with it.
variation in the ability to abstract the relevant from reality to a conceptual model, and in using the model to compare	Variation in the ability to use models	Shorter name

or apply to other situations.		
Variation in ways to study how components interact	Variation in the ability to use models	Similar, but a shorter name

Consideration on Hierarchy

In this iteration was the first time in which I considered to define a hierarchy between the dimensions of variation. Since I was using Marton's framework, the goal was to identify repetition, contrast, generalization and fusion phases through possible combinations of the dimensions of variation. Each of these combinations will be categories of description. The set of categories of the description describes a hierarchical awareness path of the object of learning, which in other words means that a higher level of awareness, implies that the learner can address the problem in a more powerful way.

In this iteration, I focused solely on answering what would be a path that describes a more powerful way to address the kind of problems I gave to my participants. The table has two different "big" categories of description: [1] Participants who experience addressing the problem as if it was a simple close system, and [2] participants who experience addressing the problem as an open socio-technical system. A simple close system is a system that is in isolation, and it does not receive any input from the environment. In this category, the learner is not aware for example of regulatory entities, or of bidirectional relationships with the customers. In the same way, learners in the other big category have a higher level of awareness of stakeholders and would involve them in for example problem scoping. I also have found so far that participants do some level of metacognition, but it might be difficult to judge from data.

I showed this model to my advisors, Dr. Oakes, and Dr. Cardella. We all thought that describing a path for the opening of dimensions of variation might not be enough, but it also should consider different levels of awareness within each dimension to make it more useful. Additionally, we thought that maybe metacognition was a threshold to be able to do this kind of tasks. The “v”s and “i” s were not clear for them, and it was suggested to have two different versions of the same map, and instead of v for “variant,” meaning that the dimension was opened, to write “o.” If the meaning was that the dimension was close, which means “invariant,” write a “c” instead of an “i.”. You can find the proposed hierarchy for these dimensions of variation in Table 3.26

Table 3.26 - Iteration 11 - Hierarchy between the DoV

		Dimensions of Variation							
	Description	**levels in which the interacting components considered are.**	**factual knowledge**	**the ability to use models (to understand big picture: trends, probabilities, behaviors)**	**working in interdisciplinary team (united with ways to study how components interact)**	**awareness of stakeholders**	**relevance of effective communication**	**strategies to perform problem scoping**	**ways of engaging in meta cognition.**
Problem as simple close system	All the dimensions are closed, which also mean that they are in the lowest value of awareness-variation	i	i	i	i	i	i	i	i
	Understand first level of system and the idea that they interact to reach a goal	v	i	i	i	i	i	i	v
	These three dimensions are opened at the same time. However, the features learned in low level.	i	v	v	i	i	i	i	v
	Factual knowledge, not too much need for the team. Implies	v	v	v	i	i	i	i	v

		Dimensions of Variation							
	Description	**levels in which the interacting components considered are.**	**factual knowledge**	**the ability to use models (to understand big picture: trends, probabilities, behaviors)**	**working in interdisciplinary team (united with ways to study how components interact)**	**awareness of stakeholders**	**relevance of effective communication**	**strategies to perform problem scoping**	**ways of engaging in meta cognition.**
	knowledge of models								
Problem as open socio-technical problem	Low or no factual knowledge, then a participant look for support from a team member from the discipline	v	i	v	v	i	i	i	v
	Here the problem has been given to the learner. The learner can think of a system, can track variables depending on its with different levels, and also has opened the dimension of stakeholder. Here participants can design a robust system considering the user. However, at this level, there is awareness of the	v	i	v	v	v	i	i	v

		Dimensions of Variation							
	Description	**levels in which the interacting components considered are.**	**factual knowledge**	**the ability to use models (to understand big picture: trends, probabilities, behaviors)**	**working in interdisciplinary team (united with ways to study how components interact)**	**awareness of stakeholders**	**relevance of effective communication**	**strategies to perform problem scoping**	**ways of engaging in meta cognition.**
	different kinds of stakeholders, but they are not involved in the design because they were not included in the problem definition.								
	You cannot open communication without opening stakeholders	v	v	v	v	v	v	i	v
	The learner is able now to perform problem definition, in a powerful way, the learner will involve the stakeholders he has	v	v	v	v	v	v	v	v

		Dimensions of Variation							
	Description	**levels in which the interacting components considered are.**	**factual knowledg e**	**the ability to use models (to understand big picture: trends, probabilities, behaviors)**	**working in interdisciplina ry team (united with ways to study how components interact)**	**awarenes s of stakehold ers**	**relevance of effective communic ation**	**strategies to perform problem scoping**	**ways of engaging in meta cognition .**
	previously identified in the problem definition and solution								

3.4.2.10 Iteration 12.

I considered a new dimension of variation in this iteration. That dimension was expressing variation from keeping the focus on the system, to focusing on helping to improve people's lives through the system. In this iteration, that dimension was called human-centered design dimension.

In a meeting with my advisors, we talked about this dimension. It was not clear for them how this dimension was different from working in an interdisciplinary team combined with an awareness of the stakeholders. Through this dialogue, the idea of ethics came to us. This dimension was explaining the idea of thinking about a system that could serve people, or improve people's experience of something, or the system could also be conceived as contributing to society, or even improving the living conditions of people. For example, participant 18 changed her focused from thinking in a system that can respond to tornadoes, to a system that can reduce climate change, which as a lateral outcome will reduce tornadoes. This new category was included in the outcome space, but considerations of the hierarchy among the different aspects was not considered.

3.4.2.11 Iteration 13.

This iteration has deep thought and iteration. After reading Marton's book again, I noticed that he expressed everything regarding critical aspects. I decided to study in part if my current dimensions of variation could be expressed in a way that sounds as critical aspects, and if they could also be considered as critical aspects of the object of learning, which is “addressing complex socio-technical systems.” Accordingly, I re-stated the sub-question on seeking dimensions of variation, to “what are the critical aspects of addressing complex socio-technical systems?”

Two of the dimensions of variation, I studied deeper here, were those related to models, since I knew it as a key aspect, but still, describing its variation was not having a sound argument. Accordingly, these two dimensions of variation were considered: “Variation in the ability to use models (to understand the big picture: trends, probabilities, behaviors)”, and “Variation in the levels in which the interacting components considered are.”.

As expressed above, I studied each dimension of variation using the wording of critical aspects instead. I asked myself “Does it sound as a critical aspect of addressing problems at all?”. Accordingly, “levels in which the interacting components considered are” did not sound to me as a critical aspect. However, the ability did. Then I seek in the data the reasons why the participants used models, when do they use them, how do they do it, how do they use them.

Participants in the study used models for different purposes. In task 2, they were supposed to be able to abstract the components and first, match them to a model of behavior in time presented in the graphs, and second, propose future behavior in the future. The interview also asked them to think about similar problems, which intended to ask them to model the problem and transfer it to a different problem. Also, the modeling of systems is usually performed to study behavior across time. According to this, the critical aspect would be related to how much the learner use models to understand or make sense of the problem; to think about the possible course of actions, and in case they have models for intervention. The name for this aspect in this iteration will be modeling.

Regarding problem scoping, that is recognized as a design activity. However, does not sound as a critical aspect. It still has aspects that are key for this study's skill and fit inside problem scoping. One of these aspects is the awareness of the iterative nature of problem solving. Another is the awareness of the overarching systems engineering design process; that is usually composed of a current system in place, an ideal system and a gap that needs to be addressed. All of this under certain constraints that should be satisfied with limited resources.

I revisited the idea of variation in factual knowledge, as well. Factual knowledge allowed participants to focus on details while being able to see their contribution to the whole. Accordingly, they were able to switch back and forth from the details to the big pictures and vice versa. Accordingly, this aspect will be called part-whole relationships.

Variation in working with the team. Transformed to Power relationships when working with others and for others. It made sense to make this change, especially trying to cover beyond working with the team, to work also with stakeholders at different levels.

Variation of stakeholders also changed to awareness of stakeholders. Here, some factual knowledge or knowledge of the business is needed. The main idea is that the participant gets a higher awareness of the stakeholders that are impacting with the system, and of those who can create constraints to it, or provide resources for it.

Communication did not get any transformation. The aspect will be called Effective communication.

Variation in human-centered design. After the conversation with my advisors, this dimension was transformed to Ethics, meaning that all the scope of the system should go beyond the goal fo solving a problem, to think about how the system could be tackling the causes that go beyond the nature of the problem.

Considerations of hierarchy

The table shows the new considerations of hierarchy. It goes from working alone, to working with others, being the latter more advance than the formers. You can find this outcome space, with the different categories of description, in Table 3.27.

In the meeting with my advisors, we thought about the modeling dimension, and they also asked me how the idea of complexity, thinking about systems of systems, is represented, or if it is necessary to think in another critical aspect that expresses it.

Table 3.27 - Outcome Space Iteration 13

	overarching Systems Engineering problem solving process	Iterative nature of problem-solving	Modeling	Long term thinking	Part -whole relationships (details vs. wholes)	Power relationships when working with others, and for others	Stakeholders awareness	Effective communication	Ethics
1 - problem address in isolation, with no tools	c - means not awareness of what it means to address a problem in a social context as an improvement	c - means no iteration	C - means two variables - cause effect.	c - means short term thinking	c - means no connection between them	c - means hierarchical relationships	c - means consideration of customer needs based on own perceptions	c - means unidirectional communication	c - means for the systems design
2 - Learner is in the world of models - uses models to make sense of reality	c	c	o	c	c	c	c	c	c
3 - learner thinks about problem solving as improving the current situation. Use models for understanding of current situation and ideal situation	o	c	o	c	c	c	c	c	c

4 - create better conceptual problem representation and solution by incorporating ideas from different stakeholders	o	c	o	c	c	c	o	c	c
Study how parts (especially stakeholers) impacts the solution	o	c	o	c	o	c	o	c	c
5 - Solution ideas are tested across time	o	c	o	o	o	c	o	c	c
6 - solutions tested across time incorporating the stakeholders visions. Different perspectives of time imply scenarios and iterations. Still everything is models of the world	o	o	o	o	o	c	o	c	c
Input from stakeholders starts to be accepted and process it	o	o	o	o	o	c	o	o	c
Consideration on how the solution could impact society/climate change, etc	o	o	o	o	O	c	o	c	o

Start working with others in the different stages. Still not thinking about the benefit for the society	o	o	o	o	O	o	o	o	c
Ideal way to address problems	o	o	o	o	O	o	o	o	o

3.4.2.12 Iteration 14.

In this iteration, I read again participant 7, participant 24, and quotes from several participants. I also reviewed my notes regarding their notes.

Effective communication. I revised this dimension especially because it was conceived with the idea of covering the need to tailor the documents the participant thought was relevant to show to different stakeholders. This description was short because it was not covering another kind of responses. This was in part my thought process:

> What about those who thought about designing a system that responds according to with different inputs, or in other terms scenario planning. Or those who were creating documents that they had to share with other units? Or passing supplies through the supply chain? I guess that communication, is one of the components of this aspect. Should that aspect be some tailoring stakeholder outcome tailoring? (My journal. April 2016)

Modeling. Expressing the variation in this area was still challenging in this iteration. When I did this iteration, these were some of the approaches:

- Use of models: I found that participants did not use models, some others used models to understand problems, some others used them also to think about solutions, and finally others who also had models to implement them.
- I also saw a variation in how they use models when thinking about a similar problem from task 1 and task 2. For example, there were students who in task 1, proposed "similarity" with other problems regarding the kind of problem they were solving: a design problem, or any problem in general. Others proposed the similarity regarding "bunch of stuff" or different components and disciplines who needed to work together to address the issue interrelated. Finally, another way in which participatns described

similarity was regarding similar behaviors. This is my thought from that time, written in my journal notes, about how to describe the variation in this dimension:

> How is this different? One is the use of models for problem solving. Another could be a transfer of models to different contexts. The latter idea on transfer could be better applied in the critical aspect part-whole relationship, especially because it is this understanding of the details and being able to see the whole what allows them to transfer to another problem. (My journal. April 2016)

I decided to post-pone this dimension and study it furhter in the next iteration.

Ethics dimension. Almost from the beginning I noticed in the data that, some participants in Task 1 defined the goal of the system focusing on making a more reliable and resilient system while others focused their attention on the welfare of people. There was another participant discussing climate change, which made her seeing the problem from a completely different perspective. I thought at the beginning of my data analysis that it would be a good idea to separate the participants that were seeing the reliable and resilience system from those who were seeing the system in benefit of people. However, that was not the approach followed, because here I was hoping to be focused on understanding the critical aspects of the object of learning. Still the idea was there, but it was not clear for me how to describe it.

At the beginning of May, I attended the INCOSE (International Council on Systems Engineering) Academic Forum – Systems Engineering for all engineers. There, one of the presenters made me remember what I read once from Herrscher's book (Herrscher, 2003), that the topic related to ethics is connected with the idea of the boundaries the learner defines for the system under her consideration. The example that made me think on this was the case of the airplane that landed on Hudson River presented by one of the speakers. He asked: “what if there was a failure of the system?”, and the answer was, “it depends on the goal of the system”, which means, was it a system designed for not failing (in which case we are concern about the airplane), or a system with the goal of keeping people alive in case there was a malfunctioning of the machinery (in which case was successful). To this case, I added: “The goal could also be defined as a system that will take people from one place to another safely, in which protocols should be added to help people reach their final destination if their health and psychological state allow them to keep traveling.” Therefore, I defined the ethical dimension as:

> When there is an ethical dimension considered, the boundaries of the system are set by the learner, according to the responsibility she wants the system under her consideration wants to assume. Accordingly, in this iteration, this dimension will talk about boundaries in terms of the hard part of the system, which means “make” better its performance numbers, or if boundaries are shifted to include a socio-technical component, or if boundaries are shifted to study the lifecycle, which is so far the three boundaries I found so far in the data. (My journal. May 5 2016)

3.4.2.13 Iteration 15.

In this iteration, I did new considerations on hierarchy seeing the quotes. I found for example in the data that stakeholder awareness could start sooner than I thought since there were quotes from undergraduates from the firsts years who stated that it was necessary to think of different systems in case the people were out in the field, or if they were in buildings. It was plausible to think that participants may know from early stages that there were users, which may mean opening this dimension of variation. Still, it there was a need to have a real experience with users and a real one working with others, in at least a participative way, to move forward in that dimension. Likewise, I also found that participant 03 talked about ethics without opening or being deep in other dimensions I thought it was necessary to open first. It confused me and then I thought about Marton's idea of opening of dimensions not necessarily in a lineal way. I changed the outcome space to reflect this alternative path, which confused my advisors. My thought at that time was that a two dimensional model cannot reflect going in a higher number of dimensions. A Further iteration was needed here.

Long-term thinking: I decided to revise this dimension because first, it was just a true/false dimension, and there were for me other references that participants made about time that was not included clearly in any other dimension. For example, there was one quote that showed that there were different ways in which a learner can think of time, from being thinking in the short term, to be able to recognize that there could be short and long-term thinking. This awareness of time was an evidence of opening vs. close within the dimension. However, another consideration of time was not included, and it is relevant because it will allow the system's boundaries to be moved. In that way, the learner will be using time as a variable to study different possible scenarios or outcomes. For example, this was clearly shown by references to simulations made by participant 11.

In this iteration, the outcome space was again two dimensional, and in the form of a table. Columns were the dimensions of variation, and rows were expressing the different categories of description of experiencing addressing the engineering complex socio-technical systems. See this outcome space in Table 3.28. Cells in blue color represent a dimension that is opened in the learner awareness, while cells in yellow represent dimensions that have been already opened in the learner awareness. Titles in brown are showing titles that were changed from the previous iteration.

Table 3.28 - Outcome Space after Iteration 15

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
problem address in isolation, with no tools	c - Means use of someone's interpretation of a model. 1 - means two variables - cause effect.	c - means no connection between components and whole	c - means consideration of customer needs based on own perceptions	c - means no iteration	c - means unidirectional communication / No tailoring	c - means short term thinking	c - means not awareness of what it means to address a problem in a social context as an improvement	c - means hierarchical relationships	c - means for the systems design
Learner is in the world of models - uses models created and interpreted by others to make sense of reality. No awareness of direct users. Cause effect models with no users.	o	c	c	c	c	c	c	c	c
Divide and conquer. Aware of parts contributing to	o	o	c	c	c	c	c	c	c

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
the whole, but not emergence.									
Still model user, and with a lineal understanding of how the world works. Awareness of direct users, but as part of the model (e.g. just solving task 2, thinking in right/wrong answer).	o	o	o	c	c	c	c	c	c
Learner gets better at modeling.iterating to find the right answer.	o	o	o	o	c	c	c	c	c
Learner gets better at modeling. Iterates to find the right solution, and think about different alternative solutions according to	o	o	o	o	o	c	c	c	c

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
customers' needs defined by the learner based on their experience (task 1. solution if people are in a building vs. if they are on a farm).									
Same as before, but thinking also in higher limits for the system to be a focus on helping people (task1).	o	o	o	o	o	c	c	c	o
Better at modeling, iteration, and long term thinking. Haven-t thought about different alternatives according to different possible users	o	o	o	o	c	o	c	c	c

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
Think about possible solutions in a longer term. Opens the ethics dimension, (task 1. helping people coming back to normal. In task 2, finding alternatives to reduce workers' unhappiness)	o	o	o	o	o	o	c	c	o
Learner thinks is needed to identify right problem, as moving from current system to an ideal system. Use of models for identification of current system in place.	o	o	o	o	o	o	o	c	c

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
Create better conceptual problem representation and solution by incorporating ideas from different stakeholders. Interactive relationship with others, asking for opinions of others (e.g. when working in teams with others, validating with them. Thinking mainly in a robust design, not going beyond the limits of the system in the boundaries of it.	o	o	o	o	o	o	o	o	c
Consideration on how the solution could impact society/climate change, etc.	o	o	o	o	o	o	o	c	o

	Modeling	Part -whole relationships (details vs. wholes)	Stakeholders awareness at different levels	Iterative nature of problem-solving	product tailoring (instead of effective communication)	Time thinking	overarching Systems Engineering problem solving process	Power relationships when working with others, and for others	Ethics
Hierarchical way in the relationships with others.									
The ideal way to address problems. Working with others in a participative way, considering long term impacts of the system (ethics and long-term together), using models to observe the possible impact of decision making.	o	o	o	o	o	o	o	o	o

3.4.2.14 Iteration 16

This iteration was necessary because neither I or my advisors were happy with the hierarchy proposed. Monica asked for especial cases, and it was difficult for me to explain them, were these cases combination of quotes, or were these expressed by single participants. This iteration was necessary.

I performed this iteration in two directions. In the first one, I wanted to revise the different features, levels or values in each dimension of variation and revise if the names were expressing the variation within. In the second, I wanted to propose a hierarchy between the dimensions of variation that could be defendable based on evidence.

<u>Studying the dimensions of variation</u>

<u>Systems modeling:</u> There were three ideas, one, asking what the quotes were telling me about [1] the kind of models a learner could use, and another, [2] how or why do they used models. [3] The third was related to the key characteristics a learner abstracts from a problem to transfer to another similar problem. Regarding [1], these models were not comparable. I had quotes talking about first order mathematical models, others about predictive models, others about a manufacturing model called lean manufacturing, another using the systems engineering design process model. Accordingly, I chose to think about [2], and look for connections with [3] since it was plausible to think that a way someone use models, is related with the way to think about similar problems.

I proposed 4 levels in this dimension regarding the use of models. In the first one, the learner is a user of the interpretation of models made by other people. Opening the dimension implies that the learner goes beyond other people's interpretations and makes their own. However, in this interpretation, the learner not always see the interactions between the components of the model simultaneously. Level A, higher level, the learner sees these interactions simultaneously. A higher level, B.1 is considering these interactions across time, idea that has its own dimension of variation. Finally, in a level B.2, an alternative to B.1, we can see that the quote implies only studies the interaction, but sometimes defines a learner's one, or going to details of the model, criticized it, and eventually modified it.

Problem rightness. In iteration 15, I included the idea of "seeking for the right problem" inside the category of knowing the overarching systems engineering problem solving process. However, this was partially excluding the possibility of searching for the problem with experts, or searching for it in data, and also searching for it with the owner of the task. That is why I decided to change the name of this dimension and include these other values in it. The variation perceived was in terms of the learner's perception of where she needs to go to ask for the right problem. The dimension was closed when the participant jumped immediately to seek a solution. It was opened in the learner awareness when she wondered if it was the right problem. The first level [A], means that the learner believes that the owner of the task has the right problem. It could be me, or it could be the imaginary person who is hiring her to address the task. The level gets higher whenever the participant "seeks harder" for the right problem. From data collected by asking experts, to finally ask the different stakeholders.

Time as a factor: This is the other dimension in which some differentiation beyond open and close was defined. dimension is closed when the consideration of time is made in the short term. It gets open when they realized that time is relevant and gets higher when the participant described the long term.

Ecosystemicity awareness. This name was created to address the idea identified as being able to recognize that there were stakeholders at different levels which were also describing the awareness of being immersed in different systems. In this regard, I perceived that some quotes regarding stakeholders showed the need to identify them conducting a study, which implies an effort to find them. Others were just assuming who the stakeholders were. The former would be the most advance level while the latter will be the lower one.

Product Tailoring: This dimension speaks about the awareness a learner has of the need to create products tailored according to the kind of stakeholder. This dimension was studied in detail and I found that there were two possible ways of growing. One in which the learner considers the user, and another in which the learner is aware and focus also on other stakeholders' needs.

Documentation. I found that there were three participants who mentioned documentation. They were from industry and were three of those that exhibited in the interview high expertise. It will be a dimension with two states: close and open.

The other dimensions were mostly stable regarding its name, and the variation they were embracing.

Hierarchy in iteration 16

Defining a hierarchy focusing only in the quotes was difficult because it was necessary to study the context in which the quote was generated to see what other dimensions were opened at the same time. It was difficult to think about this simultaneous opening of dimensions, without thinking in the whole transcript, which would allow me to have a better way to argue about this simultaneity.

Accordingly, I decided to assess each participant determining which dimensions they opened and in which level. After this assessment, I expected that a comparison among all the participants could allow me to establish a sound argument that explains a hierarchical relation among the different dimensions.

For this assessment, I went through the transcripts from each participant, and focused on identifying clues that allow me to state if a dimension was opened, and in which degree. In Figure 3.4, you can see an example of such assessment for the first 14 participants.

	product tailoring					
	status	A - awareness of the need	B1 - studying user and make solution for user	B1.1 - involve users and make a solution with them	B2 - identify stakeholders and make a solution for them	B2.1identify stakeholders and make a solution with their representatives
Column1	**Column29**	**Column30**	**Column31**	**Column33**	**Column34**	**Column35**
01-P01-IP01-En-M	oB2				x	
02-US01-03-En-F	c					
03-US02-03-En-F	c					
04-P02-IP02-Sp-F	c					
05-US03-01-En-F	oA	x				
06-US04-02-En-M	oB1		x			
07-US05-03-En-M	oB1		x			
08-P03-IP03-Sp-M	oB1		x			
09-P04-GS01-En-F	c					
10-P05-IP04-En-F	oB2				x	
11-P06-EF01-Sp-M	c					
12-US06-03-En-F	oA	x				
13-P07-IP05-En-M	oB2.1					x
14-P08-IP06-En-M	oB1.1			x		

Figure 3.4 - Assessment of first 14 participants for dimension product tailoring.

After assessing each participant's transcript, it was necessary to create a way to see the whole picture regarding my participants. Therefore, I created a condensed table showing the result value for each participant dimension assessed. The table created as result of this process can be seen in Figure 3.5

	Systems modeli	Problem rightness	iterative nature	Time as factor	Part-whole	Ecosystemi city	Power	product tailoring	Documenta tion	Ethics
	status	status	status	status	status	status	hierarchich al (closed)	status	status	Closed
03-US02-03-En-F	oB1	o1	oA	oB	oA	oA	c	c	c	o2
04-P02-IP02-Sp-F	oB	oA	oB2	c	c	oA	oB	c	c	o2
05-US03-01-En-F	oA	c	c	c	c	c	c	oA	c	c
06-US04-02-En-M	oB1/B2	o2	c	oB	oA	oA	o2	oB1	c	o2
07-US05-03-En-M	oB	oD	c	c	oA	oA	o2	oB1	c	o2
08-P03-IP03-Sp-M	?	?	?	oB	oB	oB	o2	oB1	c	o2
09-P04-GS01-En-F	oB2	c	c	oC	oA	oA	o1	c	c	o2
10-P05-IP04-En-F	oB1	o3	oB	oB	oA	oB	o1	oB2	o	o2
11-P06-EF01-Sp-M	oB1/B2	o	oB2	oC	oB	oA	oB	c	c	o1
12-US06-03-En-F	oB1	c	oA	oC	oA	oA	c	oA	c	c
13-P07-IP05-En-M	oB1	oD	oB1	oB	oB	oB	oB	oB2.1	o	o2
14-P08-IP06-En-M	oB1	oD	c?	oB	oA	oB	oB	oB1.1	o	c
15-P09-EF02-En-F	o B.1/B.2	oD	oB1	oC	oB	oB	oB	oB2.1	c?	o2
16-US07-01-En-M	o B.1/B.2	oB	c	oB	oB	oA	c	c	c	c
17-P10-EF03-En-F	o B.1/B.2	oD	o	oC	oB	oB	oB	oB1.1	c	o2
18-P11-GS02-En-F	oB/B1	c	c	oC	oA	oA	c	c	c	o1
19-US08-04-En-M	oA	c	c	c	c	oA	c	c	c	c
20-P12-IP07-Sp-F	oB	o	c	c	o	oA	oB	c	c	o2
21-US09-03-En-F	oB	c	c	c	c	oA	c	c	c	o2
22-US10-04-En-M	oB1/B2	c	c	oC	o	oA	c	c	c	o2
23-P13-IP08-En-M	oB	c	o	oA	o	oA	c	oA	o	c
24-P14-IP09-sp-F	oA	oB	c	oA	oB	oB	c	oB1	c	c
25-P15-IP10-sp-M	oB/B1	c	oB2	oB	oB	oA	oA	oB1	c	c

Figure 3.5 - Whole picture of participants' dimensions of variation

Moving the dimensions left to right or vice versa regarding the amount of dimensions opened by participants, and participants up and down regarding the amount of dimensions of variation they opened during the interview, were the activities I did in this step for finding a hierarchical relationship among the DoV. With this movements, I started to see patterns. I found that the most plausible order in which the dimensions of variation were opened was: [1] Modeling, [2] Ecosystemicity, [3] Ethics, [4] Part-whole,

[5] Time as factor, [6] Power, [7] Iterative nature, [8] Problem rightness, [9] Product tailoring, [10] documentation.

This order was different than the one I proposed in iteration 15: [1] Modeling, [2] Part-whole, [3] Stakeholders awareness (similar to ecosystemicity awareness), [4] Iterative nature of problem solving, [5] Product tailoring, [6] Time thinking, [7] Overarching systems engineering design process, [8] Power relationships when working with others, [9] Ethics. The new version of this hierarchy made more sense than the one in iteration 15, and it was easier to explain. You can see this new result in Figure 3.6.

	Systems	Ecosystemicity	Ethics	Part-whole	Time as factor	Power	iterative nature	Problem rightness	product tailoring	Documentation
	status	status	Closed	status	status	hierarchichal (closed)	status	status	status	status
Column1	**Colu**	**Columr**	**Columr**	**Columr**	**Columr**	**Column26**	**Colu**	**Columr**	**Colu**	**Colur**
02-US01-03-En-F	oA	c	c	c	c	c	oA	c	c	c
05-US03-01-En-F	oA	c	c	c	c	c	c	c	oA	c
19-US08-04-En-M	oA	oA	c	c	c	c	c	c	c	c
21-US09-03-En-F	oB	oA	o2	c	c	c	c	c	c	c
22-US10-04-En-M	oB1/B2	oA	o2	o	oC	c	c	c	c	c
18-P11-GS02-En-F	oB/B1	oA	o1	oA	oC	c	c	c	c	c
16-US07-01-En-M	o B.1/B.2	oA	c	oB	oB	c	c	oB	c	c
12-US06-03-En-F	oB1	oA	c	oA	oC	c	oA	c	oA	c
09-P04-GS01-En-F	oB2	oA	o2	oA	oC	oA	c	c	c	c
04-P02-IP02-Sp-F	oB	oA	o2	c	c	oB	oB2	oA	c	c
20-P12-IP07-Sp-F	oB	oA	o2	o	c	oB	c + o	o	c	c
03-US02-03-En-F	oB1	oA	o2	oA	oB	c	oA	oA	c	c
11-P06-EF01-Sp-M	oB1/B2	oA	o1/2	oB	oC	oB	oB2	o	c	c
23-P13-IP08-En-M	oB	oA	c	o	oA	c	o	c	oA	o
08-P03-IP03-Sp-M	?	oB	o2	oB	oB	oB	?	?	oB1	c
25-P15-IP10-sp-M	oB/B1	oA	c	oB	oB	oA	oB2	c	oB1	c
24-P14-IP09-sp-F	oA	oB	c	oB	oA	c	c + o	oB	oB1	c
06-US04-02-En-M	oB1/B2	oA	o2	oA	oB	oB	c	oB	oB1	c
07-US05-03-En-M	oB	oA	o2	oA	c	oB	c+?	oD	oB1	c
17-P10-EF03-En-F	o B.1/B.2	oB	o2	oB	oC	oB	o	oD	oB1.1	c
14-P08-IP06-En-M	oB1	oB	c	oA	oB	oB	c? + o	oD	oB1.1	o
01-P01-IP01-En-M	oB1/B2	oA	o2	oA	oB	oA	oB	oB	oB2	c
10-P05-IP04-En-F	oB1	oB	o2	oA	oB	oA	oB	oC	oB2	o
15-P09-EF02-En-F	o B.1/B.2	oB	o2	oB	oC	oB	oB1	oD	oB2.1	c?
13-P07-IP05-En-M	oB1	oB	o2	oB	oB	oB	oB1	oD	oB2.1	o

Figure 3.6 - Outcome space showing the progression within dimension of variation after iteration 16.

3.4.2.15 Iteration 17

This is the last iteration performed in this study. This time, the focus of the iteration was to verify the dimensions of variation that the participants opened during the interview, and re-arranged if necessary the hierarchical relationship between the dimensions of variation. This was necessary because I found in an aleatory checking that some participants who I thought were opening dimensions of variation were not, and also detected some others who did. Consequently, I revised all the 25 participants' transcripts, and sought for evidence of dimension opening in each section. Some of the changes were:

- Participant 05-US03-01-En-F. The dimension product tailoring was considered opened for this participant because she thought about a "best way to warn people", and then she mentioned "a siren". She did not mention this idea anymore, which made me considered that the meaning was not on tailoring the solution for different users, but in developing a general one that could work for everyone.
- 21-US09-03-En-F: In the first iteration, this participant was assessed with the product tailoring and iterative nature of problem solving dimensions as closed to her awareness. However, I found that she mentioned in her interview about reaching students using text or e-mail because that is the way in which a warning system would be more effective to reach most of them. This was an evidence of awareness of product tailoring, the first level. Likewise, I assessed her as having the iterative nature of problem solving dimension closed. In my second focused-on-assessment reading, I found at the very end that she mentioned that she would go back to check if she was

answering the question asked. That case is an evidence of the lowest level of awareness on the need to iterate.

Similar findings were identified in transcripts from participants 03, 04, 09, 11, 12, 16, 17, 18, 19, 23, and 24.

Since several assessments changed, participants were shifted up and down according to the number of dimensions they opened, and this re-arrangement made the hierarchy to be changed.

Since this is the last iteration, I will not show here the results from this iteration, but you will find them in the results section.

3.4.2.16 Iteration 18

This iteration was performed after several weeks of using the terminology in iteration 17. A brief revision was performed to make the name of the critical aspect System's Ethics more descriptive of the data, which was describing that the participant was thinking in different boundaries for the system under their consideration. Accordingly, the new name proposed for this critical aspect was Systems Boundaries. Similarly, I performed another iteration on the systems modeling usage category. I found that talking about the use of simple systems and simple models, and studying one variable at a time for the first feature, and the use of complex models and complex systems, and studying the interaction of two or more variables at a time for the second feature, were closer descriptors of the data in that aspect. It was also necessary to change its name to make it more descriptive of the use of systems / models for addressing the tasks. I chose Systems /Models Usage as this critical aspect final name.

3.5 Conclusion

In this chapter I presented how I designed the study that allowed me to find answers to my research question. I presented the different types of phenomenography I used, and how did I do the data collection and the data analysis. Additionally, I presented the considerations I followed to ensure quality in my study regarding validity, transferability, objectivity and reliability. In the following chapter, you will find the results, in which first, I will describe the dimensions of variation, and later, the categories of description represented in combinations of dimensions of variation opened in the learner awareness.

CHAPTER 4. RESULTS

In this chapter, you will find the final iteration of the data analysis. You will find a hierarchical set of nine categories of description that explain how a given learner could develop her ability to address Complex Socio-Technical Systems. As I presented in Chapter 3, a category of description is composed of a set of critical aspects and critical values that the learner has opened at a certain time. The critical aspects are the dimensions of variation that I perceived when I experienced the variation in the data, having as the background of sameness the interview. You will find in this chapter three sections. First, a section explaining each dimension of variation. Second, a graphical representation of the outcome space. And third, an explanation of the different categories of description.

4.1 Critical aspects of Addressing Problems in Complex Socio-Technical Systems

In this section, you will find a detailed description of the critical aspects that a learner needs to learn (or dimensions of variation that a learner needs to open) to address problems in engineering complex socio-technical systems in a powerful way.

4.1.1 Systems / Models Usage

The purpose of this critical aspect identified as a dimension of variation is to explain the different features regarding the use of sysetms / models by learners that were identified in the data. A model, "is a system for interpreting, explaining, describing, thinking about and designing … another system" (Adams & Layton, 2008). The Systems Engineering Body of knowledge cites thirteen different kind of models, that can also be interpreted as systems: Formal, informal, physical, abstract, descriptive, analytical, hybrid descriptive and analytical, domain-specific, system models, simulation and visualization. This dimension is "closed" to the learner's awareness when she is not aware of the possiblity of using models to address the complexity of socio-technical systems. In the data, I found that one of the features within this dimension is that learners could just use the output of systems / models developed by others. The other two features I observed with regards to systems / modeling usage were that some participants modeled the problems given in tasks 1 (interpreting, explaining, describing, thinking and designing) using "simple" systems/models (e.g. two variables at a time), while in tasks two they were not considering the variables (outputs of subsystems clients, manufacturing area, inventory, manufacturing workers) simultaneously. Other feature describes that participant were using "complex" (e.g. three or more variables at a time) models or systems in task 1, and were considering the variables in task 2 simultaneously. Finally, the data showed another feature that I consider as a higher one within this dimension of variation because it requires also reflection with regards to the limitations and behavior of the system that was abstracted from the data that was given to them in the two different tasks. In this feature, the learner use previous learned models as cognitive tools to compare and contrast the problem given, with what they already know from the models previousley learned, and in that way, monitor her understanding of the problem, and propose actions regarding the conditions given to create new models, or change the conditions of the current ones.

Participants in my study were aware of the possibility of using models which means that the dimension was not closed in this study participants' awareness.

4.1.1.1 Users of model/system outputs developed by others.

This is the first feature identified in the data regarding the opening of this dimension of variation. Quotes representing this category shows mainly the use of models and interpretations made by others with a greater expertise. Here the participant is interested in the output because she expects that she can use that information for her model. The system / model then, is seen as a black box, because the participant is not interested in how it works, but only in getting the information that comes out of the model. This use is especially notable in task 1, in which there was a need in several of the participants to gather information regarding the natural phenomena, especially the one they can use to predict the occurrence of a tornado.

In the following quote, participant 01 recognizes the importance of having information about the probability of occurrence of an event. While participant 01 does not explicitly talk about "probability" as model usage, probabilities of natural disasters are determined based on models that are created by weather experts.

> 01-P01-IP01-En-M: So it is the probability of occurrence of the event and the severity, that is important

> … Yeah, because you have to first know the probability of occurrence and the severity of any disaster even that can occur, because the response should, I mean should [inaudible] with the severity, right? (lines 120-121; 149 - 151)

Later in the interview, the participant explained that this predictive data would be developed based on past data, which I would argue can be used by a weather expert to create a predictive model.

01-P01-IP01-En-M: this probability of occurrence is obtained from past data, recorded data, as how frequently the disaster occurs and then what was the effect of the disasters that occur in the past, from there, you can know some probability of occurrence, OK? (lines 158 – 162)

Another example is the following quote from participant 12. It shows that this participant is interested in having in her team someone who understands weather patterns; these patterns, are identified by modeling elements from the real-world. While participant 12 does not explicitly talk about models, it is implicit that the expert would develop predictive models for tornadoes in the area.:

> 12-US10-06-En-F: The first thing is probably figuring out how often tornadoes happen. In order to figure out the frequency of tornadoes you would need someone who is an expert in weather, or who understands weather patterns when tornadoes would occur. Tornadoes usually occur in the summer; there is certain weather happening. To have an expert who knows that is a change has been happening, more fronts coming through, it would be helpful to know that …. (lines 57-60)

As you see, this participant intends to use interpretations made by weather experts to get the tornado frequency, which is a relevant information for her. She does not understand the weather patterns, but that she needs predictions with regards to where the tornado would occur, which is just the outcome of the predictive model developed by a weather expert. This was also the main focus of her need, she was not interested in understanding how the model works, but she was in the outcome of the predictive model.

Similar expressions of the need of predictive information (i.e., output of weather models), are expressed by several other participants. For example, in the following statement participant 19 asks for predictions with regards to the time and place the tornado would happen. It is unclear how these predictive models would be created.

> 19-US08-04-En-M: First step, I think we need to predict what time and where the disaster will happen (line 72) …
>
> Because I think the first step is avoid people hurt in the disaster and avoid … injured in the disaster. Because if we can predict where it would happen and when it would happen we can organize people leave from that area Avoid people the deaths and injury (lines 142 – 144)

The quote shows that this predictive information is a first priority for the participant because he mentions that predictive information about the disaster would be his first step. This participant shows this need also in the following quote when working on task 2:

> 19-US08-04-En-M: Like what I say, if we can know how often the order will change, we can provide... We'll have a clear diagram for the production rate and the inventory if we can know. I think we can do some research on based on the previous experience, we can do the prediction (line 438).

This quote shows the need for information, that comes from models developed by previous experiences of people that could allow them to generate a prediction.

4.1.1.2 Using simple models / systems (not considering variables simultaneously)

Data that describes this feature or value in task 1 was the one in which participants were considering addressing the task 1 by building a simple system, for instance, a safe building, an alarm, a shelter, or a complicated system such as a system that involves radars and management of big data on tornadoes. The following quote from the transcript of participant 12 shows that as solution, he would build / modify a simple static system:

> 12-US06-03-En-F: A lot of time there is underground shelters. You want a safe building, so you want people to know how to design safe buildings.

Shelters and buildings can be considered as simple static systems that do not need to interact with other systems to achieve goals. Considering that the solution involves these simple systems makes the quote a valid evidence for the feature within the dimension.

For task 2, these simple systems / models usage were found when the participants studied the different outputs of sub-systems or variables necessary to address the task (order rates, production, inventory, workers) one by one, and not their simultaneous interaction.

One example of this not simultaneous interpretation of variables is provided by participant 16. The following quote shows that the participant did not consider all the interactions of interrelated variables while he worked on task 2. In this case, at least in the beginning, there was not a connection in the participant's eyes between production and inventory:

> 16-US04-07-En-M: Until the adjustment is made, there stays at a constant production rate, for not move slowly adjust thing slowly making more edge day, that one, not very organized, I don't believe that it would go about that way, sort of then at a 9 week you are going to have a jump to 55 thousand, which, scale the graph nicely at 10, 15, 25, 30, 35, 40, 45, 50, be 55, and then, filling like [sounds like grant] to make to look nice, and the units are clearly understandable, and not having to label at someone fancy I wanna just put close by 1000 for reference, I know there is 5000 with tinish.. Sort of increase .. To 5

> thousand and stay constant indefinitely. Yeah… the spread [inaudible] here is the more ways to address
>
> John: So what about the production line? How is it?
>
> 16-US04-07-En-M The production? … So production…(lines 171-183)

Solving the second task requires a problem solver to consider production, inventory and customer demand simultaneously. Inventory would increase if the production rate increases, and would decrease if the customer demand increases. What you can see in the previous quote is that the participant was focused on describing the behavior of inventory only considering the customer demand (two variables). When he was asked about production, he realized that it was important to include that variable in his observations (three variables simultaneously), which is why he said "the production?", because he was not considering it.

In task 2, there was also a social issue in regards to the workers at the manufacturing department. The morale of the workers could impact production which means that their welfare was relevant in the case. Participant 21 was aware of the need to consider the workers; however, when she thought about the workers, she did not connect their welfare to production and inventory, but thought about them in isolation.

> 21-US20-09-En-F: When I read this, I didn't know I was going to have to do this yet and I was thinking about, again, humans, how happy are my employees here? It said the manufacturing workers are not happy. That was something that stuck out to me. You don't want your employees unhappy because that's not good for your company. You can't have people quitting on you. You know you want to make your customers happy. You want to make your employees happy as well. They do the best work for you. That had nothing to do with this graph, but that was something that stuck out to me (lines 501-508).

Here, in this post-task reflection, you can see that participant 21 discusses the importance for her to have her workers happy, but at the end of the quote you can see that she said that their welfare had nothing to do with the graph. Instead, she thought about them, but not integrated into the case.

In Figure 4.1, you will find further evidence of participants Using Models/systems, this time based on deliverables. This graph was drawn by participant 02.

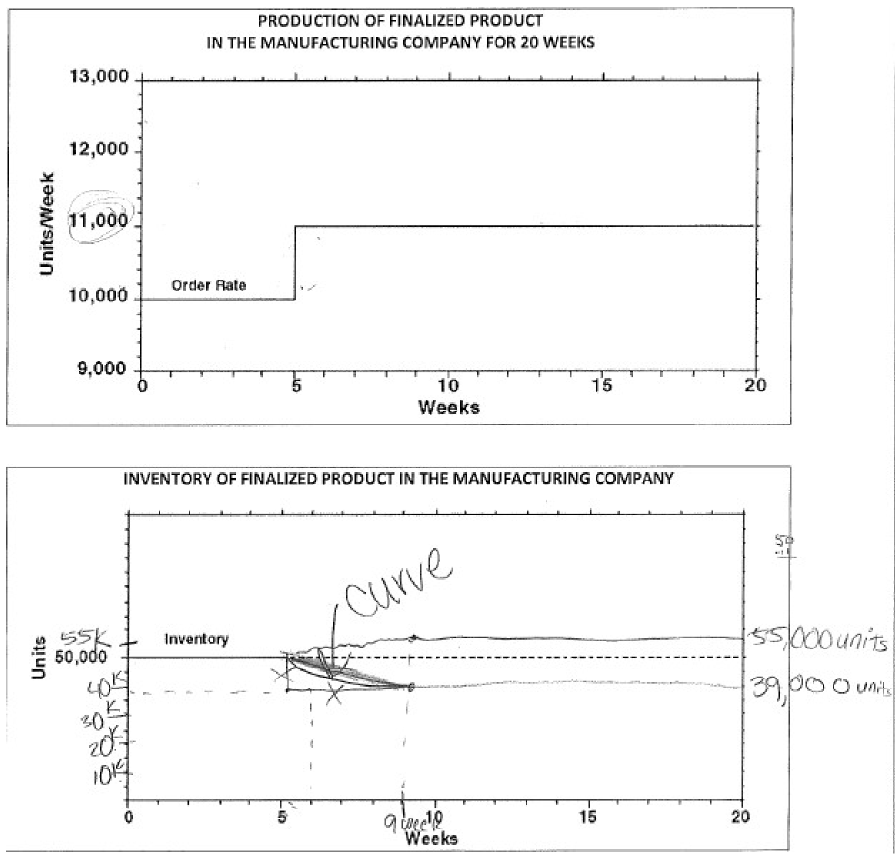


Figure 4.1 - Participant 02's graph studying variables in a non-simultaneous way.

Figure 4.1 shows that she described two trajectories for inventory. The one above shows an increase, while the one below shows a decrease. The increase is the result of the change in production, but in that case, it does not reflect the change in order rate. Similarly, the decrease is the result of an increase in the order rate, but it is not reflecting the increase in production. These two graphs show that while modeling the problem (thinking about it), the participant was considering only two variables simultaneously instead of three or more, which would have made been a better model of the phenomena in the problem. Note that in the graph the line above increases after week 5 until it reaches 55 thousand units. This can only happen if there was an increase in production. The graph below, shows an increase in demand, and a decrease in inventory. Still, the three elements of the case study (production, inventory and order rate) were not considered simultaneously.

Overall, quotes and deliverables from participants in this category show that they are not considering more than two variables at the same time while considering the behavior of the system.

4.1.1.3 Using complex systems/models (consider the interaction of more than two variables simultaneously).

Quotes that describe this feature shows that the participant in task 1 thought about a solution that includes several components that interact and need to be considered simultaneously. From task 2, quotes selected described the effort to understand the interaction of more than two variables in the problem simultaneously. These considerations mean a better understanding of the components of the system, how they are interrelated, and interactions between the components.

One example was found in the transcript from participant 11. Here the participant is saying that his solution would involve different phases, different issues to be address in each phase, and different kinds of expertise:

Original quote (in Spanish):

11-P06-EF01-Sp-M: Entonces primero todas las fases de la gestión de emergencia, segundo todas las disciplinas necesarias, entonces eso ya me daría como una especie de mapa para yo saber dónde tengo mis huecos y en cada hueco poner una persona experta, que sería la segunda fase de la actividad. (lines 136 – 139)

John: Usted hablaba de generar un mapa para saber dónde tiene huecos ... cuénteme un poco más de eso

11-P06-EF01-Sp-M Eh... no sé cómo la imagina exactamente, podría ser... podría ser un mapa tipo cajitas y flechitas o circulitos y flechitas, o podría ser una matriz, pero lo que eso me permitiría sería establecer inicialmente cuáles son todos los elementos posibles que yo puedo involucrar dentro de este equipo y luego empezar a ver dónde exactamente puedo conseguir expertos (lines 293 – 299)

Translation:

11-P06-EF01-Sp-M: So, first, all the emergency management phases, second, all the disciplines needed, that would give me a kind of map that allows me to know where do I have gaps [of knowledged or expertise], and in each gap, I would need to put an expert, which would the the second phase of this activity.

John: You talked about creating a map to know where your gaps where. Tell me more about it.

11-P06-EF01-Sp-M: I don't know how do you imagine it, it could be a kind of map with boxes and arrows or circles and arrows, or it could be a matrix, anyway that would allow me to tentatively establish what are all the possible aspects that could be involved in this team, and after that, I will search for these experts.

The previous quote describes that the participant, using in this case a matrix or a map with circles and arrows, would study the phases, the issues and the expertise needed simultaneously, which might allow him to addresses the complexity of the disaster response system more effectively than addressing them separately

A quote from participant 17 in task 2 shows an example of studying the variables of the problem simultaneously. Here she is talking about the connection between order rate, production and inventory:

> 17-P10-EF03-En-F: Inventory, ok, so 587, hold on, so there is a production that leads to inventory and orders take away from inventory… I think I am realizing, ok, inventory, production ... Orders... When these things are measured and which one is sort of like… the expression of which one is the dependent variable and the independent variable... So like in a given week, you know production you have orders and then you have inventory, so production happens, orders happens, and then inventory happens, and so …. and I am not sure if it matters when there is a particular order, but it does seem like …(lines 587-597)

As you can see, she mentioned that "production leads to inventory and orders take away from inventory", which shows her understanding of interaction between different variables simultaneously. She keeps later explains that she is thinking on a dependent and independent variable, which shows that she is thinking in the interaction between these three different variables.

The following quote from participant 14 likewise shows that he was focused on all the variables simultaneously, including also the scenario related to reaching the company's goal:

> 14-P08-IP06-En-M So they do keep the manufacturing goals, they do reach 11,000 per week of their goal, so they are able to produce that amount, they have 50,000 in inventory, so they just keep producing 11,000 per week and they meet their goal that can deliver the 11,000, the inventory of 50,000 still's there in 50,000, and the inventory does not go up or down, it just stays there at 50,000, so the dotted line becomes a solid line
>
> John: Ok, what about the production?
>
> 14-P08-IP06-En-M Well, the production is going from 10,000 to 11,000 in the fifth week , and it says here the company keeps their manufacturing goals and reaches them, so they are able to keep the ten percent increase indefinitely at

> 11,000 per units per week, meanwhile, the inventory stays at 50,000 (lines 396 - 407)

Here participant 14 had in his mind the manufacturing goals, and he discussed how the workers are able to produce the 50,000 and keep producing 11,000, which for him is the same number of units that are sold. This shows he is considering these three variables (inventory, production and demand) simultaneously.

The last example to support this feature was found in the deliverables created by participant 06. In these deliverables there is evidence of the use of a mathematical to model the changes in inventory and production. As you can see in Figure 4.2, these models are "inequations, … a statement that an inequality holds between two values" (Wikipedia, 2016) By using his modeling knowledge, Participant 06 was more precise than other participants who addressed the task without the model because he was able to calculate precisely values for inventory and production that were useful to draw a right graph. This usage of mathematical models allowed this participant to understand the behavior of the three variables in time, and through the inequations, these variables were considered simultaneously.

In summary, quotes in this feature showed that participants use complex models to make sense and address the interaction of two or more variables at the same time when addressing the task.

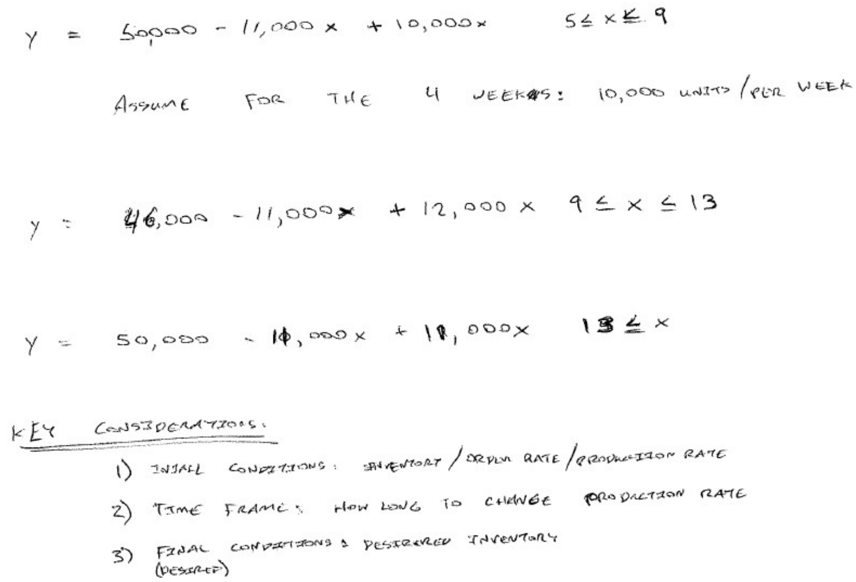


Figure 4.2 - Math model solution for task 2 developed by participant 06.

4.1.1.4 Model as a metacognitive tool – Participants evaluate the current situation and compare it and contrast it with models previously learned.

Quotes that describe this feature shows participants reflecting, questioning, or making sense of data, comparing that with a conceptual model they already know.

One example comes from participant 16's response during task 2. Here the participant considered that having inventory was a bad idea and suggested changing the restriction I gave him in the problem regarding keeping the minimum level of inventory of 50,000 units.

> 16-US04-07-En-M: I assume they want to keep more units in stock that's they're philosophy of storing extra, which isn't very wise anyway, because is proven cheaper to only have what you are selling in stock, but ok (lines 205 - 207)
>
> … therefore I made the assumption that that is what they want in the future, as their production rate is equivalent to an order rate, that the 4 weeks stall before that happen, doing a four weeks stall, the inventory drops by 4,000, but I would say Mr. CEO 46,000 extra units of inventory is substantial enough and here we are back on a track of our supply is meeting our demand (lines 241 - 244).

As you see, in the first lines participant 16 said that "it was proven cheaper" to have no inventory, which means that he already knows a model for how to manage inventory in a company, and is comparing it with the model presented in task 2. In the second set of quotes, he said that he would talk to the CEO and would explain to him that it is not necessary to increase production since the level of 46,000 units is more than enough to cover demand. This shows that participant 16 is willing to intervene to change the restrictions given in the problem, based on prior models he is familiar with, and he contrasts his prior models with the case I gave him in task 2. This is evidence of using previously learned models to address the problem given and suggest a change to its conditions.

Further evidence of this feature within the modeling usage dimension of variation was found in the transcript of participant 01. In the following quote, the participant changes the company goal of keeping 50,000 units of inventory because having inventory was a "waste.":

> 01-P01-IP01-En-M Supply, it falls 11,000, from inventory. Over 4 weeks, that will fall by 44,000. This is 44,000. It falls by 44,000. (lines 456 - 469)
>
> In inventory there[inaudible] average 6,000 at the end of the 4 weeks. There are average 6,000 in inventory, and production rate is constant 11,000, afterwards, you don't even have to keep the inventory. If that is constant sustained it just produce damage why while does keep inventory. Actually, if the inventory is the waste. It ties up money; it requires space to store it, it requires money. It costs to you to keep inventory. (lines 481 - 488)

Later the participant explained that his approach was based on the lean manufacturing model of managing waste:

> Lean manufacturing began by identify wastes and avoiding wastes. The greatest waste is inventory, inventory of all material, inventory of manufacturing products. These types have a lot of capital and you have lot of cost to keep that inventory. Keeping inventory is itself is costly. So, it not only the capital that stay up by the inventory, but also keeping it itself is a cost (lines 631 - 635)

As you can see in the first quote (lines 456 - 469), in participant 01's interpretation of the case, there was a decrease of 44,000 units of inventory. In the second part (481 - 488), he explained that inventory is waste, and later, in lines 631 - 635, he explained that his understanding of inventory as a type of waste comes from the lean manufacturing model. This set of quotes is evidence of the use of models as metacognitive tools because this participant is comparing his understanding of the problem in task 2, with what he already knows regarding inventory, and based on this comparison, he proposes changes in the system. In this case, he proposes changes specifically in the manufacturing goal of the company.

In this section I presented the evidence found in the data that supports the "systems / models usage" dimension of variation. Four features within this dimension were evident in the data: using the outcome of models developed by someone else, using simple models, using complex models to address the problem, and using models as a cognitive tool.

4.1.2 Ecosystemicity Awareness

This dimension of variation was found in quotes in which the participants discussed the presence of other related systems, which means that they knew that the system under their consideration was part of an ecosystem of systems. This dimension is closed in the learner awareness when in her thinking, there are no other systems whose outputs could impact the system she is designing. The dimension opens when the learner can see connections with other systems that could be competing for the same resources, providing services or products, be clients, or be regulatory entities. In the lower levels, there is an awareness of these systems based on previous experiences. In higher levels, the learner decides not to make assumptions and makes an effort to identify, as much as possible, all the different stakeholders and their needs regarding the system under consideration. The quotes that demonstrated participants reaching the highest level suggest the importance of going to the field and talking to people. Accordingly, it is a requirement that the power-relationships dimension (described in 4.1.8) should have been opened already, because it is necessary that the learner has learned how to work with others first, at least in an interactive way.

4.1.2.1 Stakeholders assumed

This is the first feature or value within the dimension of Ecosystemicity Awareness, and it is reached once the learner opens the dimension. The first quote regarding this feature presented here shows that the participant is aware of other systems and believes that her disaster response system could receive support or help from other systems such as local service organizations or the city government.

> 03-US02-03-En-F so, keep in mind different areas of expertise, like I guess for who I want on my team, I would probably want someone from [inaudible], someone from, like meteorology that is the study of what are. I probably want someone by the city government, or I guess is the county for county government, and, someone from a local service organization, like the Rotary Club for example (line 62 - 65)

As you can see, this participant believes that help for her system could come from the county government, who are stakeholders of the system, and a service organization such as the Rotary Club. Although during the interview the participant did not explain why she thought about those systems, it is reasonable to assume that she may be aware of the role of the county government in providing funding and/or defining the constraints and regulations that the system should abide by; and aware of the help that could come from volunteers from other organizations in case a disaster happens.

It is remarkable participant's 03 creativity and knowledge in regards of possible systems that might interact with her disaster response system, it is relevant to mention that all the ecosystem she is considering is assumed, not investigated.

The following quote from Participant 22 in task 1 is another evidence that supports this feature of stakeholders assumed. Here you will see that this participant talked about identifying the roles of different people in power, and started with a list of people or entities:

> 22-US21-10-En-M: I would say what are the expected, the Mayor of West Lafayette or surrounding townships, whoever their figurehead is. I don't know if small towns have a mayor or not … The role of the Governor. What kind of aid they can provide. The police department, what kind of services they are expected to provide in the case of a disaster or in the event that, let's say, the police department got hit by the tornado, what would we do in the absence of law enforcement after a disaster. Likewise, with the police department, I would probably put the fire department and other public services with them in regard to that.
>
> Also under police department and fire department, I'd put things like search and rescue, how those would be organized and carried out. Would we require additional volunteers or should we encourage citizens to go digging through dangerous rubble piles or should we ask them to let people who are trained in this area or could be more responsible than just digging and possibly getting themselves injured.

In the previous quote, we can see that the participant thinks in representatives from different systems at different levels. The Mayor from the city, the Mayor from other cities, the police department, the fire department and several others. This example shows awareness of being in an ecosystem. Still, all the different stakeholders he mentioned were assumed, not investigated.

4.1.2.2 Effort in identifying stakeholders in the ecosystem

The key difference between this feature and the previous one, is that instead of assuming who the stakeholders are, the quotes imply that the participants go beyond the assumptions, and do field work to identify and involve these stakeholders, which implies an extra effort.

One piece of evidence can be found in the transcripts for participant 14. In the quote selected, he proposes as part of his strategy the definition of the stakeholders, and he also mentioned an extra-effort of calling them together:

> 14-P08-IP06-En-M: first of all, try to identify and define what the problem is, and then while try to solve: "what is the problem,", and what is the user need? Who are the users and what are their needs, and who are the stakeholders.. in the problem. Who are the users and … the people who are suffering from this problem and the people who are trying to solve the problem, then I would define the stake holders in the problem and call them together, and select the ones that I believe are knowledgeable on the current, "as is" solutions to the problem (lines 22 - 25).

Unlike the participants in the previous features that were assuming who the stakeholders were, in the previous quote Participant 14 is not assuming who the stake holders are, but develop plans for identifying and engage them, as he plans to “call them together.”

The last quote I will present here for task 1 comes from participant 15. This participant said that she would go around the county, and engage in conversations with the community to identify possible stakeholders:

> 15-P09-EF02-F: Then I would get stakeholders that are involved in this disaster response system in Indiana. So, I would have to ... There's going to be stakeholders in the government; there's going to be the community, the citizens. I basically would have to go around and talk to different people, and have people on my team that are in the community. Possibly someone from the government. ... I'd be doing a lot of leg work in the beginning. I would have a lot of ... more questions about the system (lines 83 - 87).
>
> About what is exactly wanted. Who's funding it? I'd want to make sure that this project is going to ... We're going to be able to actually complete it (lines 98 - 100).
>
> So first of all I would want to gather more information. That's what I meant by doing the ground work, or the leg work. That's why I would go talk to a bunch of people to get information. Then maybe, from people I talk to, maybe some people would be motivated to be part of this team. I know that's better than me picking people. If you can talk to people that are passionate about this disaster response system, they're good candidates for the team (lines 435 - 441).

In the first quote (lines 83 - 87), the participant said that she would go around the county and talk to different people to identify some community representatives that could be worthwhile to invite to the team. After this, she mentioned she would do “leg work”, expressing an effort to identify these stakeholders, and through them, gather information she would need to in order to define the problem.

This section presented evidence of the two different features identified in the data for the dimension of variation of Ecosystemicity Awareness. The variation within these features can be described with regards to the level of effort expended to identify surrounding systems -- how much the identification of surrounding systems representatives (stakeholders) is merely intuitive, or if there are efforts in identifying these systems around.

4.1.3 System's Boundaries

The data showed that participants, when addressing tasks 1 and 2, thought about different boundaries for their system. According to the literature, the system's boundaries determine the ethics of the system (Herrscher, 2003). These boundaries determine what the learner see either as part of the system or as easily influenced by an output (sometimes also indirectly). Therefore, the boundaries impact several dimensions such as [1] "Problem Rightness" (described in 4.1.7) because the goal of the system may change base on these limits, [2] Part-Whole relationships (described in 4.1.5), because the parts identified may be different according to that boundary, and in the same way the contribution of the parts to the whole, and [3] the Ecosystemicity Awareness dimension (described in 4.1.2), because these limits will also define what systems are inside the boundaries of mine, and what systems are outside.

I found three hierarchically related ways of setting the boundaries of the system. The first one is when the participant defines its system boundaries on its performance without considering the people related to the system. In this case, the dimension is closed to the learner awareness. The second case is when the learner opens this dimension. In this case, the learner is still focused on the system's performance but now is concerned about the people within the system and the people who received its outputs. In the third case, which is a higher openness level, the learner set the boundary in the lifecycle.

4.1.3.1 Dimension closed – Boundary set in goal of simple systems

In task 1, when the learner's awareness was closed to this dimension, the goal of the system was stated by some participants as "save people's lives", and to do that, their system had components such as buildings, shelters, or warning systems. In task 2, the quotes that showed the closeness of this dimension described the need of keeping the company goals regarding inventory, and customer satisfaction. It was evident the relevance the achieve the measures and goals given to them, and to overseeing the social component included in the task.

You can see one example of this dimension closed to the participant awareness in task 1, in the following quote in which the participant 12 explains that she would work on designing safe buildings:

> 12-US10-06-En-F: We're trying to come up with disaster response systems. You would probably want to think about how you could respond to a tornado. A lot of time there is underground shelters. You want a safe building, so you want people to know how to design safe buildings. That could be a civil engineer or mechanical engineers, or other construction type people. And it would probably help to have people who designed buildings in the past that could withstand this type of disasters. If people specialized in that or done research on buildings and how to make them sturdier to withstand strong winds and debris hitting it (lines 65 - 71).

The quote shows that the participant was focused on the technological system. As you can see, she talks about underground shelters and safe buildings, and discussed the expertise needed in the team. Yet, she did not mention the customers or other stakeholders, which I interpreted as being closed to this dimension of variation.

You can see another example in the following quote from participant 16 while addressing task 1, in which he thought that shelters or alarms might compose the system:

> 16-US04-07-En-M What issues you think are essential to consider.. Ok, uhm previous existing systems in place as well as … uhm other methods that exists, and how effective they are, vs. what we have.. .always look at what exists before you trying reinvent the wheel… Uhm, clarify what exactly is a disaster response system… are we looking for shelters, or alarms? (18 - 20)

At the end of this quote the participant asks if the system would be shelters of alarms, which is evidence of the boundary of his system set in the technological system.

As I stated at the beginning of the explanation for this dimension, in task 2, having the dimension closed is related to the idea of keeping 50.000 units in inventory, and in others in keeping the same rate between orders and inventory (1/5), and in being focused on the variables, without considering the workers' conflicts that could impact the company's performance. For example, in the following quote from participant 18 you can see that the information about workers was "irrelevant", and she focused her attention on how the company should respond to the change in orders:

> 18-P11-GS02-En-F Yeah, I was trying to pick up these words here, that is why I was trying to read it because some of this information is irrelevant, manufacturing workers are sometimes not completely happy about these changes, like am I supposed to do about that, like yet, the company keeps the manufacturing goals and reaches them, I mean, I don't know if that information was there to get me to think about changing the policy, but since it seem like, likely path, so the likely path is that business is gonna continue, as usual, that is why it said the likely path is that they would reach, change, like increase their inventory to 55,000, but, now [inaudible] order, so it says suddenly and unexpectedly rises by 10% remains at the new higher rate indefinitely, that's why I said ok, let's just respond to that, that's why, ok, let's increase inventory with that, uh, I guess the more important thing was that to me the most important… was that customer orders are quite variable so that to me that's the key word (lines 323 – 331)

In the quote you can see that while the information regarding the worker's welfare is irrelevant, she explained that the goal of the organization should be to be able to respond to the change in the order rate.

4.1.3.2 Opening the System's Boundaries dimension - Setting boundaries beyond the simple system

From the data it was interpreted that opening this dimension can be seen in two hierarchical levels. In the first one, the learner recognizes that there is a social component that makes the system socio-technical. This recognition implies an awareness of the impact people have on the behavior of the system. In the second direction, participants defined the boundary regarding the lifecycle. In a higher level, there were participants who opened the dimension thinking in the socio-technical component, and at the same time, in the lifecycle.

4.1.3.2-A - Boundary set to include the social component of the system

The first direction in which the participants opened this dimension was regarding awareness of technological and social components in the system, or in other words that the system is socio-technical. In the following quote from participant 03, while in task 1, you will see that she is aware not only of the technical component but also the social component:

> 03-US15-02-En-F: I am not sure if was developing just a system and by system I mean like an electronic components and the physical objects, but instead it is what notify that way for me, the system would also include the people who are operating the system (131 - 132).

In the previous quote the participant shows her interest in the technological components such as the electronic ones, but also was alert of creating a solution in which the people operating the system was considered.

The following quote from Participant 04 also shows awareness of different boundaries that she can set for her system:

Original quote (in Spanish):

> 04-P02-IP02-SP-F: Pues es que ahorita estoy viendo un sistema como uhm... como la interacción entre diferentes procesos o cosas, pero lo estoy viendo en... en... como como ese el problema y tengo que diseñar una solución, mientras que la primera vez cuando vi sistema, pensé ya en que la solución era implementar algo, e implementar algo, no sé, con bits y bytes, si? … Entonces es diferente porque el primer sistema es el que yo pensé, que es de software, puede ser una de las soluciones para el sistema grande de respuesta … Entonces cuando dije no, pero eso es algo chiquito, pensemos en el grandote, pues ya dejé de pensar en un software… …[que] es más particular… …si puede hacer parte de la solución, de toda la solución como tal … mas no implica que sea la… …el único componente de la solución (lines 171-183).

Translation:

> Right now, I see a system as… the interaction between different processes or things, but I see it as what the problem is and I am supposed to design a solution. The first time, when I saw "system," I thought, that the solution was to implement something, I don't know, with bits and bytes, right? Then it is different because the first system is the one I thought, which is a software system, which can be one of the solutions for the big response system … then, I said no, this is something small, let's think of something bigger, then I stopped thinking about a software program… … [which] is more specific… … it can be part of the solution, of the whole solution, … but it does not imply that it is … the only component of the solution.

In the previous quote the participant recognizes two possible boundaries for her system. First, she thought about setting the boundary at the simple system level (or at the software level which is the technological component), and second, she thought about "something bigger" which means that she is aware of the possibility of setting different boundaries to the system.

Participant 04 also drew the graph in Figure 4.3, that explained how she was thinking about the boundaries of two different systems. She drew two concentric circles that represented the boundaries of the system under her consideration.

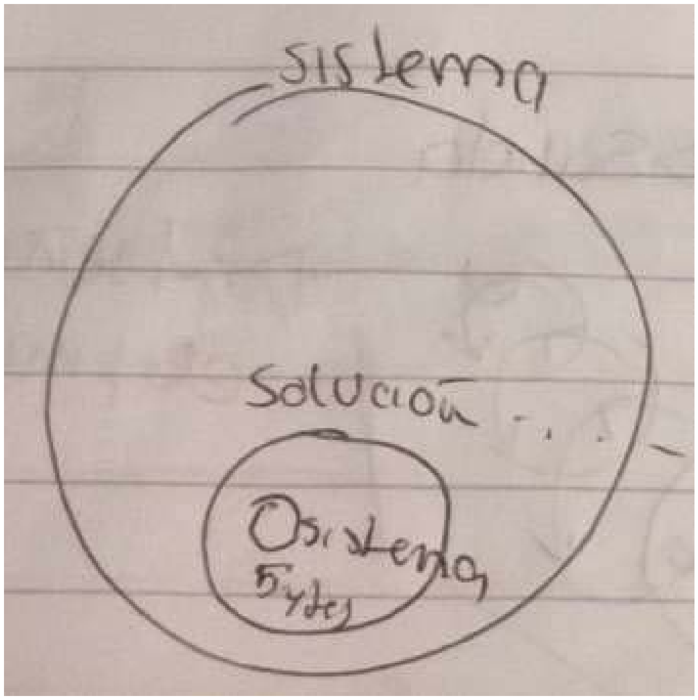


Figure 4.3 - Graphic drawn by participant 04 explaining two possible boundaries of her systems

As you can see, she called the outside circle "Sistema" (system) and the inner one "Solución" (solution), which also has inside the circle the words "sistema" (system) and "bytes". The inner circle represented the software system, and the outer circle represents the problem solution to task 1.

Likewise, the following quote from participant 17, also discusses the shift of the system's boundary for including the socio-technical component to facilitate a "broader thinking about larger range of issues":

> 17-P10-EF03-En-F: I'm thinking about this socio-technical systems perspective as engineers.. for engineers are typically at the technical side, thinking about,

> you know I'm gonna do sirens, but the socio-technical respective, broader thinking about larger range of issues (lines 91 - 93)

In this other quote, you can see that the participant is also aware of the need of including the social component, since what it comes after a tornado, was a social problem.

4.1.3.2-B - Boundary set in the system product lifecycle

Quotes that describe this feature show that the participants in task 1 set their system's boundaries in a way that allow them to intervene in the emergency for a span of time that includes actions before the tornado happen, and after the tornado. For task 2, the quotes that described this feature were those in which the participants discussed what would be likely to happen beyond the 20 weeks boundary that I gave them in the task.

The first evidence I will present for this feature within the dimension comes from participant 11:

Original quote (in Spanish):

> 11-P06-EF01-Sp-M: yo trataría de pensar en los distintos componentes que hacen parte de la gestión de desastres. Entonces empezaría por decir gestión integral o gestión holística de la atención, y para eso entonces yo diría pues que esa atención, entonces trataría de dividir en las distintas fases de la atención de desastres, entonces yo diría eh... por ejemplo, prevención, diría preparación, diría entrenamiento, diría atención inmediata y diría atención prolongada o normalización (79 - 85).

Translation:

> 11-P06-EF01-Sp-M: I would think in the different components that are part of the disaster management. I would start saying holistic management of the emergency, so I would try to divide in the different phases of disaster management, I would say training, immediate response, and long term care of the emergency or normalization.

The previous quote is showing that the participant is thinking in a system that goes beyond the emergency moment. He talked about training, which happens before the emergency, immediate response, which is held immediately after the emergency, and long term care, which is an intervention that last until the situation is overcome and people can get back to their normal lives.

In a similar direction, participant 18 in task 1 discusses boundaries set by the socio-technical component, but also she thought about the need to develop a system that not only responds to tornadoes, addressing the socio-technical component of the system, but also tackles climate change (another boundary set in the lifecycle of tornadoes):

> 18-P11-GS02-En-F: Preparation... And then there should... I guess one issue of long term thinking is tornadoes becoming more common in 2015 compared to 1915, so climate change, because if there something that we are doing as a society that is increasing risk for tornadoes it would make long term sense for Tippecanoe County to reduce its impact on that (lines 30 – 32)

Here the participant shifted her point of reference to one in which she was able to think beyond one emergency, and thought about preventing future emergencies by decreasing the number of tornadoes, which according to her are increased because of climate change. This way of thinking is an evidence of considering a longer span of time, because the participant instead of one event, is considering several events. It is also relevant to say that participants who are aware of this feature perceive circular connections, which can be seen better in the quote from participant 18, who thought that it was necessary to stop the reinforcing loop that was warming the planet, which as consequence is increasing global warming.

<u>4.1.3.2-C Boundary set on customers' experience</u>

In the previous feature, although the quotes from task 1 showed that the participant considered a longer span of time, the focus was on managing the emergency.

Quotes in this feature describes participant's attention focus on the customer's experience, which in task1implied also considering a longer span of time providing help and support to people who suffered the emergency while they get back to their normal lives. The following quote shows this feature:

> John: My question was, coming back to normal; what does it mean for you? And why do you mention it here in this scenario?
>
> 12-US10-06-En-F: Because usually when a disaster happens, usually people can't keep on going their normal routine of life, workout, go to the gym, you can't just do that because either the buildings are gone or you can get there because of the degree that's in the way. There's a lot of reasons why you can't keep doing that. Find a way to clear it faster so that people can go back to normal routine, go back to their normal life.
>
> John: Why is it relevant to you, when you mention it?
>
> 12-US10-06-En-F: I feel that's a big thing with natural disasters, being able to move past it is important. … It wouldn't be necessarily relevant to getting through a disaster, but the aftermath of the disaster is important as well (lines 192 – 206).

The previous quote from participant 12 shows that she is interested in people's welfare, or in other terms, in the customer's experience. She starts saying that in a disaster they are moved away from their normal lives and, in her words, "being able to move past" is important.

Similarly, this quote from participant 09 also demonstrates that her interest was helping people to go through this tragedy process, and help them get back to normal.

> 09-P04-GS01-En-F: Once a disaster is happening, there's nothing for us to stop it from happening but we can help those people to go through this process with more convenience or with less stress or something. I consider the process of going through a disaster as a problem and this team is designed to help people to go through this.

John: Help people to?

09-P04-GS01-En-F: Help people to go through this process, so that's how they solve the problem.

John: How does it help people go through this process? Tell me more about that

09-P04-GS01-En-F: It's like, if those people are having trouble with their lives, if their houses are destroyed, they could help them to build their houses or at least find shelter for them and if they need food or if they need water, they could provide them the resources they need and also if they are in danger, those people can save them from the dangerous places and if they need any mental help, those people could give them more confidence and help to live

John: Why is it relevant to think about help people to get people to their normal lives?

P04-GS01-En-F: Because disaster is a one-time thing. It's not like going to be spending their whole life or something. Once the disaster is over people in that area they still need to get back to their normal life. They still have their work to do where they have to go to school, or they want to go back to their own life. I think psychologists could help them to go through this (lines 177 – 90, and 227 - 230).

In the previous quote, participant 09 states that she believes that the goal of the team was helping people to go through the process of going through a disaster, which implies that the goal of the system is not focus on the system itself, but in helping the user deal with their situation, and in facilitating their process of going back to normal. This quote then is an evidence that support this feature within the ethics dimension of variation.

Quotes in task 2 in which the participants were talking about improving the situation of the company workers, which for some participants such as 01 and in the systems literature are considered internal customer. You can see one example of these kind of quotes in the following excerpt of the conversation with participant 21 in which she was concerned about the company not doing anything to make their workers feel happier:

> 21-US20-09-En-F: Again, I underlined this. Manufacturing workers are sometimes not completely happy about these changes in their production schedule and have issues with people from the sales department. Yet, the company keeps their manufacturing goals and reaches them.
>
> When I read this, I didn't know I was going to have to do this yet and I was thinking about, again, humans, how happy are my employees here? It said the manufacturing workers are not happy. That was something that stuck out to me. You don't want your employees unhappy because that's not good for your company. You can't have people quitting on you. You know you want to make your customers happy. You want to make your employees happy as well. They do the best work for you. That had nothing to do with this graph, but that was something that stuck out to me.
>
> John: Why did this stuck out to you?
>
> 21-US20-09-En-F: Because someone was not happy, and that's not good. When I see that my workers are not happy, that's a problem. However, it looks like the company doesn't really care. It says anyway, the company keeps their manufacturing goals and reaches them, which is good. They're still doing everything it sounds like on schedule. They're producing what they can.
>
> I think there's a really huge problem here if your employees are not happy. I think that that's something that there should be something done about it (lines 497 - 515)

This participant was especially concerned about the welfare of workers. She said that she would be worry about workers' happiness because, she explained, they would quit and that would not be good for the company. Her awareness of the internal customers experience as crucial for the company's success make me believe that if I would have asked the participant to address a problematic in the case, she would give priority to improve workers situation, developing a system in which the boundaries of it would consider the internal customer's experience.

4.1.4 Time as a Factor

When this dimension is invariant or closed to the learner awareness, the participant expects an immediate effect after seen an action. The literature describes this way of perceiving the world as short-term thinking.

In the following quote you will see evidence of being closed to this dimension because participant 19 described short-term sequential cause – effect relationships when addressing task 1:

> 19-US18-08-En-M: After we know the disaster will happen, the next step is to organize the people escape from the area close to the disaster will happen. The next step is to evaluate, sorry I think that the second step is to evaluate how bad the disaster. Then the next step is to organize the people to escape from that area. We may organize, the first step is to organize these people to a safe place, like what I say before and the safe place is consist of a team. After the disaster, we need to go to the destroyed area and searching and evaluate how bad the disaster again (lines 73 - 79).

This participant presented sequential "steps" to address the complex socio-technical system during the emergency. This use of sequential steps is evidence of sequential thinking, and the use of specific actions in which the final result is expected to start the next one, is evidence of short-term thinking.

4.1.4.1 Considering a longer span of time

Reaching this feature imply that the learner has opened this dimension of variation. Quotes selected that describe this feature within the dimension Time as a Factor shows that the participant is aware of the need to consider a longer span of time to address the complex socio-technical system. In task one, this longer span of time was expressed whenever the participant envisions a system that includes people preparedness, and/or the recovery of the city, and/or helping people dealing with issues such as insurance claim and/or psychologist.

The following quote shows that participant 03 is aware of two possibilities regarding time, which means that the participant had opened the dimension, because she started to consider different moments:

> 03-US15-02-En-F So, for example, like when I read that says you are developing a disaster response system, it makes me think of like, people going in after the disaster already happen to help like clean up and fix things, but for me, I guess is better like storm or disaster system would be one that cleans up, but also gives alert to people … or just awareness to the people of what to do in case of a disaster so that they are more prepared (lines 83 - 86).

Here you can see that the participant thought about seeking people after the disaster, and later she also thought about warning people that a tornado is coming. This is longer than cases in which participants discussed that their system only had a warning component.

Similarly, participant 20 also showed that she would address the emergency in this socio-technical system considering a longer span of time:

> Original quote (in Spanish)
>
> 20-P12-IP07-SP-F: necesitamos un médico, un odontólogo, no sé. El psicólogo, para apoyar a las familias en... pues que fueron afectadas después de la tragedia, psicológicamente. Trabajador social, para ayudar a reubicar las familias. El alcalde, para que pueda patrocinar el proyecto en la ciudad. Y una aseguradora para que le de apoyo a la gente que ha perdido su casa.
>
> 0:32:47 John Apoyo en que sentido?
>
> 0:32:49 20-P12-IP07-SP-F Eh... Cómo qué tienen qué hacer para file the insurance después de que pasa el desastre (lines 275 - 283).

Translation:

> 20-P12-IP07-SP-F We need a medical doctor, an odontologist, I don´t know. The psychologist, to support families in.. that were affected by the tragedy, psychologically. A social worker, to help in family re-location. The mayor, who can sponsor the project in the city, and an insurance company that can support families that lost their homes.
>
> John: what kind of support?
>
> 20-P12-IP07-SP-F: what families need to do to file an insurance claim

You can see here that participant 20 discuss that the system should help people for a longer span of time, because she mentioned for example helping people with post-traumatic attention (this can be inferred from her proposal of needing medical doctor, dentist and psychologist to support people who suffer the tragedy), also in the support that the system can provide to people when filling insurance claims.

4.1.4.2 Awareness of delays

Quotes from participants that described this feature within the dimension of variation Time as a Factor showed that the participant can recognize that the response after an action might not be seen immediately, that there might be delays between the moment in which the learner makes a decision or action, and the moment in which the effects of this decision or action can be seen.

Dealing effectively with the case proposed to participants in task 2 required awareness of delays. There, participants were asked to describe how the inventory is impacted once the order rate increases. To satisfy the new customers' order rate, it was necessary to increase production, which was not possible immediately, but only after 4 weeks.

This quote from participant 17 shows the awareness of delays this participant has, recognizing that she was not considering the delay in her analysis:

> 17-P10-EF03-En-F: ok, so In the current scenario there is an order rate, and a production rate and an inventory, so is like all these 5 weeks you get the order rate equals to the production rate so the inventory never actually changes, so you make 10,000, you sell the 10,000, you save 50,000 but you have 50,000 already. Ok so now I am going back, it takes 4 weeks to adjust the production schedule... AHA . That was the variable I was not reading, so…. Ok, so I am going to put 4 weeks up here, 4 weeks lines (599 - 603)

As you can see, the participant, after her analysis of the data given for the problem, when she realizes that there was a delay she says "AHA", which means that she is able to recognize delays and their impact.

Similarly, in the following quote participant 14 also mentioned that at first he missed the 4 weeks because he was focused on keeping the goal of the system.

> 14-P08-IP06-En-M There is fact, the very last sentence, the company keeps the manufacturing goals, and reaches them, is kind of a… to me I just read that is like they need to meet their goal immediately rather than it will take them 4 weeks, that was a little bit, I missed the point that it will take them 4 weeks to adjust the production schedule during which they would have to deliver the extra 1 thousand per week taking them out of inventory, yeah (lines 482 - 485).

The previous quote shows that the participant can recognize the impact of delays because he said: "I missed the point that it will take them 4 weeks to adjust the production schedule". Still, once he mentioned it, he immediately offered an explanation of what would happen with the inventory level for those 4 weeks in which the production cannot be increased. This evidence contributes to the understanding of variation within this dimension.

4.1.4.3 Simulations as a tool to address the long term

This feature was found only in the transcript from participant 11. Still, since reknown systems' authors such as Sterman and Richmond have advocated for the use of simuations as a crucial tool to address complexity, it was included as the highest feature within the dimension. In the following quotes from participant 11, you will see how this participant thinks about the use of simulations to "play" with the variable time, which allowed him to study the behavior of the different components of the system in the long-term:

Original quote:

> 11-P06-EF01-Sp-M Digamos que el tiempo aquí es una... es una variable importante, pero es una variable que no siempre tiene el mismo valor o no siempre tiene la misma eh... relevancia, es decir, es un tiempo relativo… (lines 235 - 237)
>
> Entonces lo que... es decir, es un problema desde el punto de vista psicológico por un lado, por nuestra... por la forma en que pensamos, pero también por el otro lado es un problema de administración y gestión, porque también muchos de los mecanismos de administración y gestión están pensados en causas y efectos inmediatos, entonces de alguna manera hay que complementarlos con otros modelos que permitan ver los efectos a largo plazo y por eso las... las empresas tradicionalmente han hecho planes estratégicos y proyecciones y prospectivas para tratar de ver esos efectos a largo plazo o herramientas más específicas, más tecnológicas como simulaciones o eh... tableros de indicadores de gestión, donde yo pueda jugar con las variables para ver qué pasaría con esos efectos ya no en el siguiente trimestre, sino en los siguientes 3 años, porque si yo tomo una decisión para atacar un problema ahora, podría estar generando un problema mayor mañana (lines 693 - 707)
>
> Translation:
>
> 11-P06-EF01-Sp-M: Let's say that time is here a.. it is an important variable, but not always this variable has the same value, or it doesn't have the same relevance. I mean, is a relative time … then, what… I mean, it is a problem from the psychological perspective on one side, because the way we think, but it is also a management problem, because several of the management tools are designed to consider only cause and immediate effects, then there is a need to complement them with other models that allow us to see the long-term effects. That is why the companies have been developed models that allows them to see the long term, or specific tools such as simulations and balance score cards where I can play with the variables in which It is possible to see what would happen with this effects not only in the next term, but in the following three years, because if I make a decision today to tackle a problem today, it might be creating a bigger problem tomorrow.

In the previous quote, participant 01 explained that it was necessary to study critically the amount of information received, and the impact of decision that needed to be made. For him, time was a variable that was important to include in the simulations, which can be inferred from what he says about time as a relative variable that could have different values, and his argument explaining that there are management tools such as the balance scorecard that are used to study the effect of variables in the long term, as the participant said, for example three years instead of one.

In this section I presented the different features that were found in the data regarding Time as a Factor. The three features found as representative of this dimension of variation were: Considering a longer span of time, awareness of delays, and simulations as a tool to address the long term.

4.1.5 Part-Whole Relationships

When the learner's attention is focused on the parts, and forget how these are connected to make a whole, this dimension is closed to her awareness.

In the following quote participant 17 explains what it means to be focused on the parts. My comments inside the quote are in [brackets]:

> 17-P10-EF03-En-F: So on the team would be somebody who was helping us to think about not just preparing the system itself like the system is just [the parts:] the technology or the system is just the policies and procedures

In the first paragraph she stated that the system was just technology or policies and procedures, which I interpreted as parts.

4.1.5.1 Considering the relationship between the parts and the whole.

The following quote from participant 17 is a continuation of the quote presented above. This time the participant talked about the need for going beyond the parts.

> 17-P10-EF03-En-F: but the system also has this [the whole:].. You know what's your training component built into what are these [inaudible] training themes I will built in to it, Because if people don't know how to play their roles in the system [the parts again], and we are assuming that their people in the system, then the whole thing is gonna fall apart [the whole]… (lines 197 - 201)
>
> systems typically are thought sort of narrowly, and it is easy to focus on the parts like [thinking about the parts], the tornado is coming we warned the people and then we help them like make sure that they are not dead, but there is [switching to the whole] the way before the system like are we all prepared for it, do we have all the stock in place, do we all have the [inaudible] did we store enough water, and there is a part after the system part uh, can we get the health care we need, can we get our insurance claims done, can we get counseling and move on in the right direction … (lines 221 - 225)

As you just see, the participant continued explaining that there were other components that needed to be considered such as preparedness of individuals and entities. I interpreted that idea as being aware of the existence of a bigger picture, and at the same time, having in the range of attention the parts.

Task two allowed me to see this variation in the graphs. I will show you three examples that go from being not concerned with the details, and focus on describing the general behavior of the whole, to have a very detailed graph, to be more accurate when describing the behavior of the whole. Let’s start with the graph created by participant 04 (Figure 4.4).

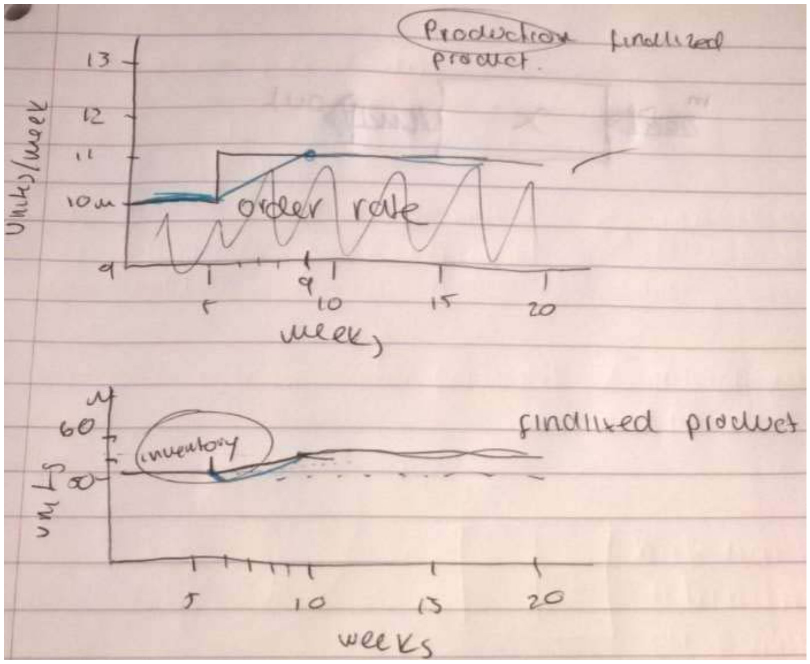


Figure 4.4 - Participant 04 showing inventory's and production's general behavior. Not showing focus on details.

The interview with participant 04 was held by skype, and the participant couldn't print the task at that moment. That is why I asked her to reproduce the graphs for task 2 by hand. Her graph had little details if you compare it with the graph created by participant 24 (see Figure 4.5). However, in the graph for participant 4, you can interpret a general behavior for inventory (which in the graph goes down and then goes up), and production (increased linearly, but not connected with the way in which inventory is changing). Yet, you would miss the details on how much the inventory decreases and for how many weeks, because these values at that moment were not in her focused of attention.

Like participant 04, participant 24 also drew the graph by hand in her skype interview (see it in Figure 4.5). She was more specific in her draw to describe the behavior of inventory. As you can see, there are detail and specific data in each axis that give specific values for inventory. This level of detail was not observable in the graph drawn by participant 04, which shows a higher understanding of the behavior of the inventory stock, and a better understanding of how in flows and out flows, and the delay impact the level of inventory.

4.1.5.2 Deeper understanding on how the details are connected with the behavior of the whole, and vice versa.

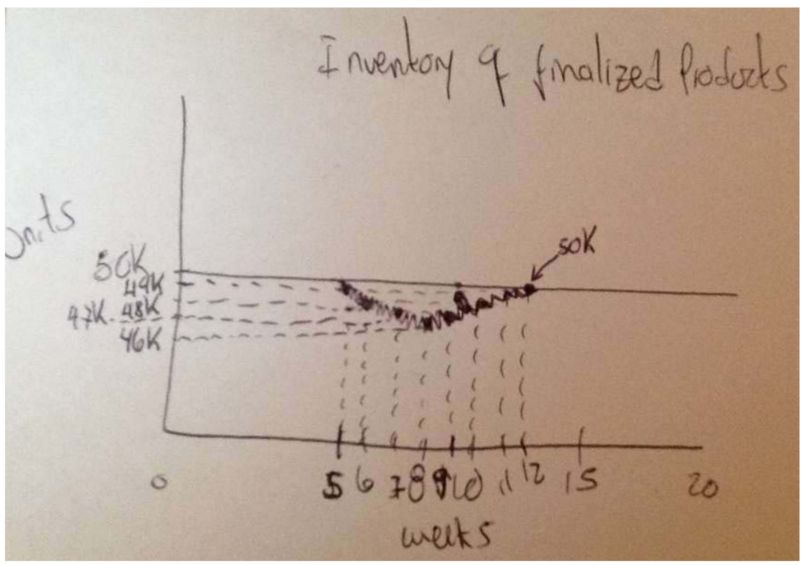


Figure 4.5 – Participant 24's inventory graphic. Detailed in the two axes: weeks and inventory

Quotes that motivated this feature were those in which the participant was able to clearly articulate connections between the parts and the wholes, and also were able to switch from the being focused in the parts, to be focused in the whole, and the other way around.

The following quote from participant 15 is one example of this feature. He mentioned the need to go beyond the parts and consider the whole, which implies awareness of the parts the whole, and their relationships.:

> 15-P09-EF02-F: I guess I've learned enough to ask a lot of questions. People, sort of, put their blinders on, and do things in a very narrow way. They're not really looking at the whole picture. All these people are basically wasting their time and energy working on things that aren't going to go anywhere. Because they're too narrowly focused and don't understand the big picture (lines 334 - 338).

Here the participant explained that to address the complex socio-technical system, it is necessary to look at the whole picture, and understand where the whole is going, this to be sure that each particular effort from people is not a waste of time. As you can see, the participant gives priority to the relationship between the parts and the whole.

A further example of this feature can be seen in the following quote from participant 08 in which he is talking about how he would address task 2:

Original quote (in Spanish):

> 08-P03-IP03-Sp-M Bueno, ahí hay que arremangarse y fijarse bien en los detalles y cómo va ese curso de las facciones, las partes del proceso fabril, y que esto no es todo una [inaudible] continua, si no que tiene sus altibajos. De repente podemos estar acolando la producción de una parte cuando sobran por otro lado y están en [inaudible] manubrio de un automóvil es una fracción ínfima del costo de todo material. Pero si no los tenés no sabes los costos ….. tienes que estar pensando exactamente dentro del tiempo del plan de producción, cuándo tenés que tener la... el manubrio, cuándo tenés que tener las ruedas, cuándo tenés que tener las tuercas de las ruedas, para cuándo tenés que traer las tapas de la rueda, y todo eso. Es un tema vital, es fundamental... eh... y todo de [esa infomación es necesaria para saber] lo que realmente está pasando (lines 658 - 673)

Translation:

> 08-P03-IP03-Sp-M: ok, there we have to roll up the sleeves, and observe all the details and how the different parts of the process are going, because this is not a continuous production, but on the contrary, it has its ups and downs. We may be

> in overstock of one part, while there is excess of another. For example, the steering wheel of the car is a very small proportion of the whole car, however, if you don't have it, you don't know the expenses, you have to be thinking inside the production time, all the time. When are you getting the steering wheel, when are you getting the wheels, the tires, the tire's screws. and all of this is a transcendental to know what was going on.

In this quote the participant explains that the details are very important because one malfunctioning single piece in the process impacts the whole production. He also explains regarding knowing the details in production is necessary to be able to be more precise in regards to the manufacturing time and it can be inferred that knowing this details contribute better to see their impact on the whole.

4.1.6 Effort in Product Tailoring (Related to Final Solution)

Beyond defining the right problem, producing the right outcome or the right product is necessary for addressing socio-technical systems effectively. Having this dimension closed in the learner awareness means that the learner is not aware of the need to tailor the outcomes of the system according to the customer or stakeholder needs, preferences.

One evidence of having this dimension closed is shown by Participant 02. There, the participant thinks about a general system that is "easy to understand for everyone involved" and simple to operate.

> 02-US14-01-En-F Yeah, I feel like having a system, like having a tornado alarm would be simple, so the complex would be having every single room, every single big room, having like a little digital box spring, where it starts beeping, and then someone in the room will have to punch in a code, and then the person who was punching in the code will have to tell everyone to get out and then punch another code to make sure that everyone did leave, so the head person will not like, everyone on this room is evacuated, and I feel that be complicated, just because what if no one in the room knows the code number, or they forgot and put in the wrong one, they could punch in the code to mean something else, you know, so and then the person, the head person will have to make sure that

> every single room has everyone evacuated and if not, then, he would have to go in there, and I feel that be, complex (lines 91 - 98).

In the previous excerpt, Participant 02 is in a position in which she is thinking in the solution, and she is proposing characteristics for the product. For example, she said that the system should be simple, and easy to use, and that is why having the user to punch a code might be a mistake. This decision is made based on her own pre-conception and opinions on what is easy to use.

On the contrary, opening the dimension implies first, awareness of the need to Tailor Products, and: [1] Identification of direct user's needs, and working with them in an interactive or in a participative way, being the most powerful the latter. [2] Or at a higher level, identification of all the needs the different stakeholders have, and work with them in an interactive or a participative way. Reaching this level within the dimension, requires opening the dimension of ecosystemicity, and the dimension of power relationships.

4.1.6.1 Awareness of the need to tailor the solution

The following quotes show evidence of awareness of the need to tailor the solution for task 1 to satisfy the customer needs. The quotes allow me to infer that these participants are aware of this need of tailoring, but think on the solutions with nobody's help.

The first example comes from the transcript of the interview that was held with participant 12. She proposes to tailor the solution in regards of the place in which the people could be when the tornado is coming:

> 12-US06-03-En-F: It would also be helpful to know more about the demographics of the area; who's living there, and what kind of daily lifestyle people have. Because if people have more of an outside... If they're outside all the time, you might need a different type of response system, rather than if people are more inside, working most of the time in buildings. You could probably have a different type of response system (lines 79 - 83).

Her phrase in regards the development of two different systems, one for people who are inside buildings, and another for people who are outside, is evidence of her awareness of this need to tailor the solution.

Participant 07 is also aware of this need, because, according to him, the system would fail if it is not designed taking into account the people from the area:

> 07-US12-05-En-M: and finally be the local official or representative would be good to make sure that the other people are able to make their expertise more tailor to the particular area that we are in.
>
> John What is the issue there?
>
> 07-US12-05-En-M I guess the best way to say it is that sometime you know, things look good on paper, they kind of fail when you put them into practice because when you take expert planning in things that are mathematically or theoretically sound, and you put them with people, sometimes it doesn't always work. Sometimes, just the people factor… (lines 38 - 44)

Here you see that the participant explains that any solution should be tailored to the particular area in which the system is intended to be developed, especially to deal with what he called the people factor. This means that in his view the customer needs should be taken into account, otherwise, the participant explained, things would not work even if they are theoretically sound.

4.1.6.2 Studying the user and making a solution for them:

Quotes that described this feature allowed me to infer directly or indirectly that the participant, instead of assuming the customer needs, as it was presented in the previous feature, conducted different studies to understand the customers and identify what they need. One evidence of this can be seen in the following excerpt from Participant's 17 interview transcript:

> 17-P10-EF03-En-F: so we need some people who represent the social kind of component, that is talking to people who would be able to, part of the people who live in Tippecanoe County understand the values they have, understand what matters to them, understand their fears, try to appreciate how much money they will be willing to spend, how this kind of system implies understand What people take to… so modify behaviors to appreciate how they would respond or they respond willingly or they are resistant to certain kind of things, uhm.. So there is a bunch of social components… so people cross over talking about the kind of systems that are possible, and I will assume that there are lots and lots of responses, and I am trying to figure out what the responses are, and trying to understand them using all the other data to picked out what are the different responses (lines 54 - 62).

Here the participant is saying that she would talk to people in the area to gather information that allow her to understand them better (their fears, appreciate if they want to invest in the development of the system, and what it takes to modify behaviors, etc). Although the quote is not explicitly saying that this information would be used for designing a system that can be accepted by the customer, it can be inferred (also because the participant was developing the system, and customer needs identification was one of the steps she considered in the design process to develop her system earlier in the transcript).

4.1.6.3 Involving the user and making a solution with them

There were no quotes in which the participant discussed only this feature, since participants either did not mention involving the customers, or talked about the customers and stakeholders as if they were different. I will cite here the latter because it shows that there is a differentiation of the user as different from the other stakeholders. This quote from participant 14 mentioned the need of incorporating the users in the process so the participants "buy the process":

> 14-P08-IP06-En-M: Who are the users and what are their needs, and who are the stakeholders... in the problem. [inaudible] are the users and … the people who are suffering from this problems and the people who are trying to solve the problem, then I would define the stakeholders in the problem and call them together, and select the ones that I believe are knowledgeable on the current, "as is" solutions to the problem ... Then I would down select maybe 6 or 7 of those or 8, the smallest numbers of stakeholders call them together in a setup a group of engineering people …whatever users stakeholders to begin to attack the problem, and come to some consensus (lines 23 - 29).
>
> what is the "as is " system and what is the "to be" the desired system, what are we trying to come up with, what are we trying to solve and come up with a solution to and make sure we got a clear definition of what that is, (lines 38 - 40)
>
> … Okay, now once we have a conceptual solution we need to make sure we have the resources to go forward and get the approval of our stakeholders to that the solution and make sure that the stakeholder is buying the process and the result of the process performing the trade study, once they have bought to the result and we use maybe a Delphi technique to get consensus where we have the different stakeholders have outlier opinions, outlier analysis of this options and we try to converge on the best solution by having the stakeholders involved and presenting their outlier versions of what their concerns are and we try to maybe even to have a re-vote or we do another trade study where we try to converge maybe on one optimum solution that is accepted that is close to the true optima, and then do a downstream evaluation. Ok, so once we are at that point, and we have user buying, then, then we go ahead and perform a requirements analysis … (lines 59 - 68)

This excerpt shows that the participant would like to invite to the team a group of users to the team, and a group of other stakeholders, representatives of those who are interested in solving the problem, as the participant said. This is an evidence of the disposition that the participant has to involve the user in the design process.

4.1.6.4 Identifying all the stakeholders, studying them, and making a solution for them

The difference with the two previous categories presented before is that in this case, the participants were talking about stakeholders, implying with this term users and representatives from other systems that are exchanging with the system that is design. The following quotes from participant 10, shows that she will run a study to find the needs, and then, she and her team will create a solution after hearing the voice of the different stakeholders.

> 10-P05-IP04-En-F : the first thing would be understand who the stakeholders are, and probably have an explicit list of stakeholders would be the result of that analysis, and then probably a needs analysis after that, stakeholder needs analysis (lines 30 - 31)
>
> John: Let's talk about the stake holders, can you elaborate on that?
>
> 10-P05-IP04-En-F: Well, when you come out with a new idea you want to make sure that all the people out there, impacted by the new idea, that their voice is heard, so there is a stake holder from Spain, there is this stake holder who [inaudible] lose [inaudible], so it is impacted by it, maybe there is some regulatory stakeholders that wanna make sure that environmental policies are followed, etc., so
>
> John: Why are they relevant to you?
>
> 10-P05-IP04-En-F: Because the solution you might come out with, could be incomplete if you don't understand the full set of stakeholders that are involved and impacted, uhm, because the solution that you might come out with could be

> incomplete if you don't understand the full set of stakeholders that are involved and impacted (lines 119 - 127).

In the previous quote the participant mentioned that it is necessary to identify the stakeholders and conduct a needs analysis because it is important, she says at the end, to design a system that responds to the needs of the "full set of stakeholders that are involved and impacted". Still, in this quote the participant did not mentioned inviting the stakeholders to be part of the design team, which is an important part of the next feature or level.

4.1.6.5 Identifying all the stakeholders, involving them, and making a solution with their representatives

The following quotes from two different participants show evidence of reaching this level. The first quote comes from participant 15 who shows that she would include in her team people from the community and the government to be able to develop a product that fulfills the needs of these stakeholders:

> 15-P09-EF02-F: There's going to be stakeholders in the government, there's going to be the community, the citizens. I basically would have to go around and talk to different people, and have people on my team that are in the community. Possibly someone from the government. To make sure we follow all the potential federal, state, regulations in place (lines 84 - 88).
>
> I would want to understand the impacts to the community, of this disaster response system. That's really why I'd get the community involved as well. So they can sort of, buy into the solution. It would have to build a solution that they could accept. There's no use in me coming up with a system that they don't like. They're not going to use it. I want my stuff to be used. I don't like wasting my time (lines 101- 107).

Participant 15 said in the first excerpt that she would identify the stakeholders by talking with different people and she would invite some of them to be part of the team. In the second quote, she said that it is her interest to understand how the community could be impacted by the system, and that she would like to involve the community buy into the solution.

The second set of quotes comes from participant 13. In the first paragraph , the participant is talking about the solution to the task I gave him. However, it is in the second part, where there is a strong evidence of reaching this level within this dimension. There, he discusses the need to involve the stakeholders to be able to deal with the politics:

> 13-P07-IP05-En-M: Well because you could go off and do all kinds of good stuff, do all kind of good works. If the stakeholders don't believe that they … You are taking a major risk that when you get down at the stakeholders will agree with your answer. Chances are very good of depending upon how you look at it. If you do not include stakeholders, chances are very high that you did not … That the stakeholders may not like some of your recommendations when you come out at the end. The way to minimize that and to get people to buy in and accept your recommendations when the team is done is to include the stakeholders upfront. It takes a little bit more time, harder to do, messier work, but in the end it gives you a higher chance of success (lines 182 - 190).

> 13-P07-IP05-En-M: In the case at [company name] it was a situation where you were dealing, how to say this … You have lots of engineers who can go design a rocket, and if you tell them what you want, they can go design, they're a good lot they could do that. However, it had a certain budget constraint that had to live within, it had political constraints that were being imposed by the executive branch as well as the legislative branch, so the White House and Congress. Once it got into the policy part of the discussion, the policy part of the problem was driven ... Had multiple different stakeholders with very much opposing views. That really became the hard part. The technical part to design the rocket was almost easy. It was how do we work our way through these political stakeholders, and some want this and some want that, or by the way they don't even want to talk to each other. We're kind of the middle people trying to pull all this together. (lines 723 - 735)

As you see, in the first quote cited for participant 13, he is discussing the need to involve the stakeholders in the design process from the beginning, or in his words, "up front", to get their acceptance. The participant knows that this takes more time and that it is harder to do, but in the end, it is worth it, because that increased the chances of success. In the second paragraph, Participant 13 discusses that there were other stakeholders who were representatives of the system's constraints, and since most of the times they have different views and interests, it is key to involve them in the design process.

4.1.7 Problem rightness (Related to Problem definition)

When this dimension is closed, the learner jumps into a search of a solution and thinks that the problem statement I gave them (or given by the task owner), is the right problem to solve. Opening the dimension means that the learner thinks about finding the right problem. She is a also aware of the need for identifying the resources she has and the constraints of the problem. However, she also needs to grow, from thinking that the owner of the task (me or the hypotethical person who would hire her to do the task) knows what the problem is; to consider that it is necessary to find the right problem. Moreover, defining the right problem can be done with experts, or in a participative way, including users and other stakeholders, which for this dimension is the most advance feature.

4.1.7.1 The learner believes this is a non-real problem, and the owner of the task knows what the problem is

The following quote shows the feature in which the participant thinks that I know what the right problem is:

Original quote (In Spanish):

> 04-P02-IP02-SP-F: Qué factores serían importante considerar en el diseño de este sistema de respuesta a desastres? Por favor utilice hojas {inaudible}. Uhm... Cuando ahí tu me estás preguntando... Yo te puedo hacer preguntas?
>
> John: Claro.
>
> 04-P02-IP02-SP-F: Cuando tu dices sistema, estás hablando de un sistema general, cierto? (lines 94 - 97)

Translation:

> 04-P02-IP02-SP-F: what are the issues you need to consider in the design of a disaster response system…uhm, when you are asking me here to… Can I ask you questions?
>
> John: Yes, sure.
>
> 04-P02-IP02-SP-F: When you are saying system, you are talking about a system in general, right?

You can see that the participant asked me clarifying questions regarding the tasks, in this case, she specifically asked me the kind of system 'I was asking her to design. Asking me for clarification on the task implies that she believes that the task is not real but an exercise, and that I know what the right problem is.

Participant 17 also shows that it is possible to think that the task was not real but an exercise in which the owners of the task could have the right problem:

> 17-P10-EF03-En-F: Well certainly I would make sure I did not go into the assumptions, uhm, in who is being asked to do this at the end of the conference maybe I am misunderstanding, maybe this is actually an exploratory exercise, that is not a real, sort of flat excersise for this county (lines 452 - 454)

As you can see, participant 17 says that the she did not want to make any assumption on "who is being asking to do this", leaving the door open for a problem that is not real but an "exploratory" exercise, in which case, the right problem would be the one that was presented by someone in the conference.

4.1.7.2 The learner seeks for the current system in place and identifies possible flaws that can be addressed to make it better.

In this case, the learner will seek the right problem in the existent gaps in the current system in place. Participant 06 for example, will seek for past history, seeking to understand how the community has responded in the past:

> 06-US09-04-En-M So the current system in place, from that knowledge and, there would be past history on previous tornadoes that have struck this area, from that information we can understand how we responded in the past, were there any issues with that response, were they effective, were there any cassualites or anything among these lines, based on that
>
> John: Why is it relevant to consider that?
>
> 06-US09-04-En-M: I think you need to stablish the base line to where the project just wanna go, so starting with this is what we have and establishing where do we wanna go from there, is, I think important
>
> John And why is it important?
>
> 06-US09-04-En-M: If we look at brand earth , if we start from nothing, we may come out with a disaster response system that's, may not accommodate for everything that has already been accounted for, if there is a pretty, if there is a system that is already in place, the new system would have to, or new ideas for the system would need to be incorporated to improve its functionality (lines 71 - 82)

In the previous quote, the participant proposed that to address the right problem, it was necessary to identify and study the current system in place, and use it as a "base line" for the new one.

4.1.7.3 The learner, to identify the right problem, seeks the big picture

For this level of awareness, quotes that were selected proposed that to find the right problem, improving the current response was not enough. The quotes show that the participant wanted to get more information about the context to understand the big picture. For example, in the following quote from participant 4, she states several questions that allow her to get a bigger picture of the problem:

Original quote (in Spanish):

> 04-P02-IP02-SP-F: Porque... porque... porque... a mí... o sea si a mí me ponen algo así, yo me pondría a investigar primero como, o sea, hacer investigaciones, entonces como parte de... del diseño, sería investigar qué ha pasado o cuáles son o por qué es que debo hacer esto, o sea, cuál es el motivo, si es que esto es muy frecuente, o no pasa, o es que cuál es el problema de los tornado en Indiana. (lines 113 - 117)
>
> John: Entonces eso que acabas de decir, sería lo primero que haces, verdad?
>
> 04-P02-IP02-SP-F: Sí, como... sí como una investigación para determinar realmente por qué, o sea, como la necesidad o algo así, y así saber realmente cómo atacar el problema. Porque pues es que hacer un sistema de respuesta de desastres es muy general y si... ya me lo están poniendo particularmente para un estado, pero igual no sé por qué. Entonces necesito saber la causa para poder dar una solución a eso (lines 120 - 128).
>
> John: Tu dijiste estudios, estudios en qué?...
>
> 04-P02-IP02-SP-F: Uhm... investigaciones como de eventos pasados, de qué... como históricos, como qué es lo que ha pasado, por qué ha pasado, eh... qué tan frecuente es fenómeno, uhm... cuál ha sido la respuesta que ha tenido la comunidad qué es lo que está haciendo el gobierno al respecto... eh... cuál es apoyo que se le está dando a la gente cuando ocurre un tornado... Uhm... qué... qué... qué sitios geográficos está afectando el tornado, cómo se está determinando si hay forma de determinar que un tornado se aproxima, eh... (lines 272 - 276)

Translation:

> 04-P02-IP02-SP-F: Because… if a problem like this is given to me, I would first do a research like, I mean, as part of the system design, I would research what has happened, or what are those, or why am I supposed to do this, or what is the motivation, if these tornadoes are happening too often, or they never occur, or what is the problem of tornadoes in Indiana.
>
> John: So, that is what you will do first, right?
>
> 04-P02-IP02-SP-F: Yeah, a first research to determine in real why, like need finding, to know better how to deal with the problem.. because creating a disaster response system for disasters is something very general, and if… they

> are situating the problem for a specific place, still I need to know the cause to be able to provide a solution to that problem.
>
> John: You said studies. Studies on?
>
> 04-P02-IP02-SP-F: research on past events, such as historic data, what had happened, why did it happened, how often is the phenomenon, how the community responded, what is the government currently doing, what is the current support we are giving to people when there is a tornado, how can you determine if a tornado is coming…

In the previous quote, participant 04 asked several questions intending to get a bigger picture before defining what the right problem was. She asked for example what has been in the past, what is the motivation, why is the need, what do they mean with “disaster response system?”. She also said that will look for information in regards of past events, and previous response to the phenomenon. The quote then is evidence that support this feature in the definiton of the right problem.

In this section I just showed you three different features within the Problem Rightness dimension of variation. These features describe how the participants go about finding the right problem to address.

4.1.8 Understanding of Power relationships when working with others, and for others

Quotes selected to describe this dimension of variation were showing the way in which the participant related with other members of the team, and with people in the community. Three different kinds of power relationships were identified based on literature from management science: Hierarchical, interactive and participative (Jackson, 2000; Lleras, 1995).

What was found was that a learner whose understanding of power relationships is closed to her awareness will relate with others in a hierarchical way. For example, in task 1, the following quote from participant 05 shows that the user thinks that people should “obey” the system, and that is why the customers should be educated or trained to follow the system’s rules. That is an evidence or hierarchical power-relationship between the learner (the system’s designer), and its customer.

> 05-US-03-01-En-F Just you know, they main part, the top thing is just to keep people safe and informed, so that, they don't do anything stupid in case of a disaster because, if there is a tornado, like, it is dangerous, yes, but if you are inside a building, like, if you are in, like the basement you wouldn't die, is not something that is too dangerous that is like, everyone would die, is something that you can be protective from, if you know what to do, that is why is just, uhm, is just important to like inform them, educate them, tell them what to do, uhm they don't want to go, so that no dead harm (lines 78 - 82).

As you can see, at the end of the quote, the participant uses unidirectional language such as “inform them”, “educate them”, “tell them what to do”, which is a language that is used to transmit commands that need to be followed. That language is evidence of hierarchical power relationships.

Similarly, the following quote also shows that the learner would work with his team in a hierarchical way. You can see that he said that each expert works for the participant, and each of them is focused on solving specific issues related to their discipline:

> 12-US06-03-En-F: In order to figure out the frequency of tornadoes you would need someone who is an expert in weather, or who understands weather patterns, when tornadoes would occur…. To have an expert who knows that is a change has been happening, more fronts coming through, it would be helpful to know that (lines 57 - 60)
>
> … A lot of time there is underground shelters. You want s safe building, so you want people to know how to design safe buildings. That could be a civil engineer or mechanical engineers, or other construction type people. And it

> would probably help to have people who designed buildings in the past that could withstand this type of disasters. If people specialized in that, or done research on buildings and how to make them sturdier to withstand strong winds and debris hitting it (lines 66 - 71).
>
> 12-US10-06-En-F: I guess it makes sense to think about who was on the team and what they do for me.
>
> John: Any reason why, you can guess?
>
> 12-US10-06-En-F: I'm not sure. If you can get the people who were helpful then you'll be able to use them to solve the problem (lines 154 - 157).

In the previous quote, participant 12 talked about issues and assigned one expert from a related discipline to address the issue. This approach implies that, when working in an interdisciplinary team, the participant does not expect to work with others, but instead, the participant's vision is that each discipline works individually on themes related to their specialty. For example, the expert in weather understands weather patterns, the civil engineer or the mechanical engineer would work in constructing safe buildings. Finally, the participant said that he would "use" the people, verb that made me think in objects or in mechanical instruments, but not in people, which is remarked in the systems thinking literature when comparing the way in which people relate to each other in the analytical thinking paradigm, vs. in the systems thinking paradigm.

In task 2, this feature was identified when the participant did not know what to do with the information I gave them regarding the manufacturing workers. For example, in task 2, the following quote shows that the participant was not comfortable with the information about the "unhappy" workers while addressing the task

> 02-US01-03-En-F Uhm, I don't know why they added that manufacturing workers were not completely happy with the people from the sales department, I feel like that added information can cause someone to over think it, or some

> people just put completely neglected. I know for me is kind of in the back of my head, I'm thinking about it like, if it's going to affect my answer (lines 281 - 283)

As you see, the information about the workers, she said, made her overthink, because when participants engage in this kind of relationships, they focus on the performance and components of the simple system, while have low consideration for the system's social component.

4.1.8.1 Learner engaged in pluralistic (interactive) power relationships

Quotes describing this category show that the participant has opened the dimension of variation and started to work with others in an interactive way. The following quote from participant 10, shows that the participant relates with the team in an interactive way. You can see that she has just collected and analyzed data, and then she validates this with the experts from the team.

> 10-P05-IP04-En-F: ok so, back to the gap analysis so the data uhm, have gaps, then probably wanna fill some of those gaps too … so fill data gaps, by perhaps more interviews or data gathering, for objective data gathering, so similar would be the objective data, the data what the tornado history is being, and you know, what the responses were, etc, hopefully that would be some sort of past analysis but if it's missing you want to go ahead and do that … Ok, and then you may want to bring together a multidisciplinary team and start identifying some issues that they [inaudible], sort of a validation of what have been gather so far, but you could have a multidisciplinary team, validate for comments on, revise the analysis gathered, … so the multidisciplinary team will validate revise, the analysis that have been gathered today (lines 40 - 47)

In the previous quote the participant said that after collecting the information regarding the current system in place, the team would have the responsibility to validate that information. Here, when the participant talks about the team, she does say that is a team job, which is an evidence of working with the team together to reach a solution. Still, it looks like the participant use the team as consultants and she is not part of the team, because she talks about the team using the third person of the plural: "and then you may want to bring together a multidisciplinary team and start identifying some issues that they [inaudible], sort of a validation of what have been gather so far". Accordingly, the relationship of this participant with the team is interactive because she created for example the needs analysis, and asked this team to validate it: "so the multidisciplinary team will validate revise, the analysis that have been gathered"

4.1.8.2 Learner engaged in participative power relationships

Quotes identified as descriptive of this feature have the participant working together with the team, and usually in the team there are stakeholders from different levels in the ecosystem. One example is found in the following quote from participant 04. In there, she says that she would have all the experts sitting at the same table interacting to find a solution together:

Original quote (in Spanish):

> John: Y cómo... qué tipo de pregunta les harías? …
>
> 04-P02-IP02-SP-F: Qué preguntan?... ah... no pues es experiencia, cuáles, cuáles, cuáles son los motivos de los problemas, entonces cómo los han solucionado, qué casos estudiaban y analizaban, cuáles... cuáles creen ellos que es la mejor solución, eh... si yo tengo una teoría mostrárselas a ver ellos qué consideran o qué factores me faltan por considerar o eh... sí qué complementen en todos los gaps que yo no sé y además... pero no les haría como preguntas individuales, sino todos juntos para ver como interac... o sea, para ver cómo llegamos a una solución o la... o evaluamos soluciones entre todos. Cada uno desde su área, pero todos interactuando... (lines 393 - 403)

Translation:

> John: And, what kind of question would you ask the experts?
>
> 04-P02-IP02-SP-F: questions… why these problems are happening, how have these problems been solved? What cases were studied and analyzed, which is the best solution according to them?.. if I have a theory, I would ask for their

> opinion on possible gaps it has, .. but I would not ask them questions individually, but to all together to see how through interacting… I mean, how can we reach a solution, or … assess solutions together. Each one from their area of expertise, but all of us interacting…

In the previous quote the participant said that she would ask the team several questions, but she will not ask questions to individual members, but to the team, to see if all together can reach to a solution. This excerpt evidences that the participant is open to work with others in a participative way, and it also supports the feature within the dimension.

Another quote that shows this way of working in a participative way with others is the following one from participant 13:

> 13-P07-IP05-En-M: Engineers will always try to solve a problem with an engineering approach. Social scientist will always try to solve the same problem with the social science approach. What you need is a combination of the two, not one or the other. What you saw me doing was try to think through the issues and do we have the right people on the team to come together to solve the problem, not just one skilled set or the other, that and if I just had one skill set for example, just all engineers, well my recommendations will be skewed to an engineering perspective (lines 327 - 333).

In the previous quote the participant explains that engineers and social scientists have different mindsets, and that the key to address a complex socio-technical system is by combining their approaches. He later explained that the key was that the team came together to solve the problem. This idea of the team working together supports this feature of understanding Power Relationships within the dimension of variation.

4.1.9 Iterative nature of problem-solving (Seek feedback at different moments to learn and improve)

When this dimension is closed, the learner is not aware of the need to seek for feedback to learn and improve. In this study, three different features that describe the opening of this dimension of variation were recognized from the data: Iterating with self, measuring performance, and systems that learn and improve (incremental prototypes).

4.1.9.1 Iterating with self: feedback at a personal level (metacognition)

Here the learner performs iteration over the problems to make sense of new information, and compare what they know with this new information.

> 13-P07-IP05-En-M: That's when I started writing this note down here at the bottom about trying to figure out what the time factor was for production, and then going in back and looking at the problem again. I said okay wait a minute there actually is probably enough information. There may be enough information here to actually draw this chart moving on the right (lines 555 - 558).
>
> 13-P07-IP05-En-M: Because I always try to get the problem, I always try to start with the simple and then work out…
>
> John: And why is that?
>
> 13-P07-IP05-En-M: Because I am a simple minded person and I can understand, I try to get into something I can understand first without a lot of extra noise, and then once I understand the basics, then I can start layering on the next levels of complexity (lines 846 - 850)

You can see that this participant wrote notes at the bottom of the page and went back to look at the problem trying to find out if he had enough information to go about it. Later in the second excerpt, the participant said that he always starts simple and then iterate, incorporating in the new iteration new "layers of complexity". These statements from participant 3 are evidence of using iteration with self when addressing these kind of complex socio-technical systems.

Another example of this personal level of iteration in problem solving was found in the transcript from participant 17. There, you see that the way in which she gets information about the rightness of her work is based on her iterative process with herself checking if she had answered the question that was asked.

> 17-P10-EF03-En-F: So I am going back now and make sure I answered the question… hehe … Ok so now I am going back, it takes 4 weeks to adjust the 602 production schedule... A-HA.. That was the variable I was not reading, so…. Ok,

You can see here that she went back to the problem statement, and by doing that she reached an “a-ha” moment, finding out that there was a variable she was overlooking. That excerpt from participant 17 is another evidence that support this feature within the dimension of variation of Iterative Nature of Problem Solving.

4.1.9.2 Measuring performance

Quotes that were selected as descriptors of this category showed that the participant sought data that allowed her to assess the current performance of the system, regarding metrics pre-defined on that purpose. For example, the following quote from participant 01 is an evidence of this feature:

> 01-P01-IP01-En-M: this team need to evaluate whether they are responding as efficiently to the problem or not, whether they are solving the problem or not, whether they have met the demand of the problem or not. I mean, there needs to be evaluation, feedback and so on...
>
> John: What is it relevant?
>
> 01-P01-IP01-En-M: Because there is no way they know that they are [inaudible] the problem, unless they give some feedback and prove it. Measurement and reporting of the actual performance of the responds should be made, otherwise you don't know how are you performing, because the responds [inaudible] [inaudible] the [inaudible] of the problem. It coint[inaudible], I don't know, one month, two months and so on. So there should be a reporting feedback, reporting, evaluation, and then a way of correcting any problems and any deficiency. So that, you attend the goal you want to, so that you respond, I mean so [inaudible]fitly to address the problem … These people who are responding to the problem are just on the side of the responding, right? ... building houses or

> whatever whatever, OK? So let's say, some uh one thousand houses are destroyed by tornado, then the plan may be to build this one thousand houses within a month or two months for instance (lines 268 - 292).

In the previous excerpt, participant 01 discussed the need of measuring “whether they are responding as efficiently to the problem or not”, sentence that show this participant awareness of the feature. Later, in the same excerpt the participant also explained the need to take actions to correct any deficiency.

You can see another example of this feature of measuring in the following quote from Participant 13:

> 13-P07-IP05-En-M: The only way to know that is to know first you have to have a baseline, what works now, or how does it work now. Then be able to say okay, if I make this change or make this improvement, how is it … What's going … How is it going to change? It may not get you to quantifiable measures, but it can get you qualitative measures at least for the improvement. Then that’s all going to be part of the decision process of are those good recommendations or not? Basically it’s … Another way to look at it is I'm trying with this, I'm trying to use … I'm trying to draw a baseline just like I would on a project management thing where I would say, okay here is our schedule, this is our baseline schedule and then we track our progress against that baseline and see how … To see how we are doing (lines 352 - 361).

Like participant 01, participant 13 also was in need to assess the system’s performance because it is “the only way to know”. He explains that it is necessary to have a baseline to be able to compare how it was in the past vs. how it is working now after the change or improvement I made. He also mentioned that these measures could be quantitative, and also qualitative.

4.1.9.3 Iterative nature of Problem Solving – Incremental prototypes or systems that learn and are constantly improved

Quotes that describe this category acknowledged improvement of the system through iterative and incremental prototyping, as it is called by participant 04. This means that in the participant's view, the product will never be final, but always suitable to be improved. In the following quote from participant 04, she mentioned the iterative and incremental prototyping:

Original quote (in Spanish):

> 04-P02-IP02-SP-F: empezamos la primera etapa de diseño, o bueno las etapas, porque quién sabe, no sé, digamos, bueno, no sé, como yo lo he vivido, siempre es como un ciclo iterativo y... de diseño ... incremental, donde eh... se plantean soluciones, soluciones y se van mejorando y complementando y obviamente ellos [los expertos] tienen que estar ahí, porque ellos son los que aportan su experiencia y su conocimiento y... y ya cuando se considere entre todos que se puede llegar a tener la mejor solución dadas las restricciones, pues sale... el diseño definitivo (454 - 460).

Translation:

> 04-P02-IP02-SP-F: We start the first design process step, or the steps, well , I don't know; the way I have lived this, there is always an iterative cycle and.. of incremental design, in which solutions are proposed, and these solutions are improved and getting more complete, and obviously they [the experts] have to be there, because they are the ones who are contributing with their experience and their knowledge, and.. and that is all, when all of us considered that we have reached the best solution that take into account all the constraints, we have the final design.

In this quote you can see that the participant discusses her approach to the design of systems. She mentioned the iterative incremental design process, starting with a simple solution that gets more and more complete. The process continues with a validation made by experts whose advice is taken as input for future versions.

This quote from participant 15 also describes her need to develop a pilot, from which she can learn and propose improvements:

> 15-P09-EF02-F: start coming up with different alternatives, and we would get input. We would use a core team to do this work, and then we would get input from a broader audience. Each step in the way. Then we'd probably ... I would probably want to identify a pilot according to this ...
>
> A pilot would mean some area in Indiana, in Tippecanoe county. You know, a small, maybe a neighborhood or something. And do some practice with this ... With the solution that we've developed. Or do some practice along the way to refine our solution so that we can ... So, that would be what the pilot would be. We would possibly get a neighborhood, or a small town in this county to agree to do the response. You know, we'll go through whatever the solution is, and then they would have to carry out the expectations of response. Then we'd see. We'd probably make certain assumptions, how much time we had. How long it would take people to do things. Then we would, basically, go validate our assumptions, and refine the system so that when and if an actual tornado does come, the system will afford the allotted amount of time for people to get into a safe situation (lines 129 - 147).

Participant 15 said that she would like to have a pilot of the system intending to validate assumptions, and refine the system outputs, so the system will be ready for whenever a real emergency happens. This quote was an example of using prototypes or pilots for iteration.

4.2 Categories of Description that Describe the qualitatively different Ways in which a learner might experience addressing complex socio-technical systems. (Outcome space)

As explained in 2.7 Variation Theory, an experience with the phenomenon is described regarding critical aspects and critical values of the object of learning. The set of experiences represented in the outcome space is called "categories of description." The critical aspects are the dimensions of variation described in 4.1. Since the most difficult learning is related to opening a new dimension of variation (Marton, 2014), I defined a set of categories of description that explained an incremental awareness of the critical aspects explained in the previous section. These categories, as I explained in the data analysis section, were obtained after [1] individually assessing every participant's whole transcript in respect of the dimensions of variation that were opened by that participant while the interview was held; and [2] arranging these transcripts' assessments sequentially from those in which evidence of the opening of only one dimension was found, to those in which evidence of all the nine dimensions was found. On the other hand, the features within each dimension were not taken into account to define if a participant's transcript belonged to one category or a different one, but I used these to study the differences in the growing in dimensions already opened once a new dimension of variation is opened, as it will be presented in the discussion section.

The categories of description that describe the qualitative different ways of experiencing addressing complex socio-technical systems are:

- Systems' modeling usage
- Ecosystemicity

- Systems Boundaries
- Time as Factor
- Part-Whole Relationships
- Effort in Product Tailoring
- Power relationships when working with others and for others
- Problem Rightness
- Iterative Nature of Problem Solving

4.2.1 Category 1: Model user

Dimensions of variation opened	**Dimensions of variation closed**	**Participants in this category**
Systems / Models Usage	Ecosystemicity, System's Boundaries, Part-Whole Relationships, Time as a Factor, Iterative Nature of Problem Solving, Power Relationships, Problem Rightness, Effort in Product Tailoring	02-US01-03-En-F 05-US03-01-En-F

Participants in this category of description have opened the Systems / Models Usage dimension of variation, but are still unaware of the other dimensions of variation.

4.2.2 Category 2: recognizing complexity

Dimensions of variation opened	**Dimensions of variation closed**	**Participants in this category**
Systems / Models Usage, Ecosystemicity	System's Boundaries, Part-Whole Relationships, Time as a Factor, Iterative Nature of Problem Solving, Power Relationships, Problem Rightness, Effort in Product Tailoring	None

Since the idea of progression in variation theory is opening one dimension at a time, learners in this category have opened the Systems' modeling usage, and the ecosystemicity dimensions of variation, both of them in the first level of awareness, which means that they might realize that it is important to consider other systems around. Still, the other categories are closed to the learner awareness. My sample does not have any participant who perfectly fit into this category.

Still, it is worth it to say that the participants in the next level would open the ecosystemicity dimension, and you will find an explanation of it in there.

4.2.3 Recognizing different boundaries

Dimensions of variation opened	**Dimensions of variation closed**	**Participants in this category**
Systems / Models Usage, Ecosystemicity, System's Boundaries	Part-Whole Relationships, Time as a Factor, Iterative Nature of Problem Solving, Power Relationships, Problem Rightness, Effort in Product Tailoring	21-US09-03-En-F

Learners in this category will have opened the dimensions Systems / Models Usage, ecosystemicity, and system's ethics, still, all of them in lower levels, which implies that they are not interpreting all the different variables or components in a system simultaneously, but at least, they are aware of other systems around that could impact their system. These systems around are limited to those in their awareness, and they believe that there is no need to seek for others. Also, since the ethics dimension might be opened, they could include in her thoughts, when thinking about a system, considerations that go beyond the hard part, or the technological part of the system: people.

4.2.4 Category 4: Recognizing time as a factor

Dimensions of variation opened	**Dimensions of variation closed**	**Participants in this category**
Systems / Models Usage, Ecosysetmicity, System's Boundaries, Time as a Factor	Part-Whole Relationships, Iterative Nature of Problem Solving, Power Relationships, Problem Rightness, Effort in Product Tailoring	19-US08-04-En-M

Learners who fall in this category have ideally learned how to consider interaction among variables or components of the system simultaneously, are aware of other systems around, have shifted their sytem's ethics boundary to consider the socio-technical component, and now they realize that there could be some consideration regarding time.

4.2.5 Recognizing wholes

Dimensions of variation opened	**Dimensions of variation closed**	**Participants in this category**
Systems / Models Usage Ecosystemicity Awareness, System's Boundaries, Time as a Factor, Part-Whole Relationships	Iterative Nature of Problem Solving, Power Relationships, Problem Rightness, Effort in Product Tailoring	03-US02-03-En-F 09-P04-GS01-En-F 22-US10-04-En-M 16-US07-01-En-M 23-P13-IP08-En-M 11-P06-EF01-Sp-M

A learner who falls into this category has grown in the different dimensions that go before, which allows her to understand how the different interrelated parts of the system, contribute to its whole. According to my data, a learner here would be better at her modeling usage by considering different variables at the same time, and understanding models that include delays. She would be more aware of other systems around, above or below, and will set the boundaries of her system typically beyond the limits of the technological system, mostly at the level of a socio-technical system, or even better, at the level of considering the lifecycle. Also, they will be more aware of the relationships between the parts contributing to the whole.

According to my evaluation of the interview transcripts, 6 participants were representatives of this category of description: 09, 22, 03, 16, 23 and also, are considering the whole, and how the parts contribute to it.

4.2.6 Recognizing the need of tailoring

Dimensions of variation opened	**Dimensions of variation closed**	**Participants**
Systems / Models Usage, Ecosystemicity, System's Boundaries, Time as a Factor, Part-Whole Relationships, Effort in Product Tailoring	Problem Rightness, Power Relationships, Iterative Nature of Problem Solving	18-P11-GS02-En-F 12-US06-03-En-F

Learners who experience addressing complex socio-technical systems in this category of description are aware of the need of tailoring the outcome of the system according to the specific needs of different users and scenarios (For example, responding to a category two tornado vs. a category 5 tornado differently). At first, these needs and scenarios are defined based on the learner's perception of them, and that is why this dimension appears sooner than others such as problem rightness, Power, and iterative nature of problem solving/validation.

4.2.7 Recognizing the need for identifying the right problem

Dimensions of variation opened	**Dimensions of variation closed**	**Participants**
Systems / Models Usage, Ecosystemicity, System's Boundaries, Time as a Factor, Part-Whole Relationships, Effort in Product Tailoring, Problem Rightness	Power Relationships, Iterative Nature of Problem Solving	24-P14-IP09-sp-F 07-US05-03-En-M

A learner who opened this dimension of variation to her awareness realizes that it is necessary to dig deeper to find what the right problem is. Participants at this category defined the problem as a gap between a “base line” situation, or “as is” system, and an objective one. As it was shown in the previous section, the differentiation was based on who the participant believed it had the knowledge of the problem, and in their need to understand the big picture of the problem.

It is interesting that most participants in my study opened first the dimension of effort in product tailoring than this one. However, I interpreted that most participants who opened this dimension, reached higher levels in the dimension of effort in product tailoring, which may imply that to provide systems that are tailored to the needs and possible scenarios, you need to have a better understanding of the big picture of the problem.

4.2.8 Giving voice to others

Dimensions of variation opened	Dimensions of variation closed	Participants
Systems / Models Usage, Ecosystemicity, System’s Boundaries, Time as a Factor, Part-Whole Relationships, Effort in Product Tailoring, Problem Rightness, Power Relationships	Iterative Nature of Problem Solving	20-P12-IP07-Sp-F 17-P10-EF03-En-F 06-US04-02-En-M 25-P15-IP10-sp-M

A learner whose experience falls into this category of description addresses the problem more powerfully because he is aware of the need to involve others in the different processes regarding the system’s design, and the right problem to be addressed. This involvement of others increases the chances of successfully create solutions that address the gaps found. Participants 20, 17, 06 and 25 opened this dimension in a participative level (highest level in power) once they have already opened and advance in the previous ones defined in my hierarchical structure.

4.2.9 Embracing continuous improvement

Dimensions of variation opened	**Dimensions of variation closed**	**Participants**
Systems / Models Usage, Ecosystemicity, System's Boundaries, Part-Whole Relationships, Time as a Factor, Iterative Nature of Problem Solving, Problem Rightness, Effort in Product Tailoring, Power Relationships		04-P02-IP02-Sp-F 14-P08-IP06-En-M 01-P01-IP01-En-M 10-P05-IP04-En-F 15-P09-EF02-En-F 13-P07-IP05-En-M

Learners who fall into this category of description have also opened the dimension of "iterative nature of problem solving", meaning that they might know it is almost impossible to have it right at the first attempt, and will be engaged in the validation of results in different stages, that eventually will create lessons learned. The differentiation within the dimension is based on how much the participant involves others in this validation or iteration. Opening the dimension implies iteration at least with the learner itself, which is related to be involved in metacognitive processes, key for understanding and learning (Bransford, Brown, & Cocking, 2000). Going beyond implies that this validation to iterate is made based on the judgement of experts. In a higher level the validation is made based on data collected about the performance in the short term, and at the highest level, the learner seeks for feedback that allows improving the system in the long term.

4.3 Graphical Representation of the Outcome Space.

Figure 4.6 is showing the results of the assessment I did to the transcripts of 24 participants. For this assessment, ‘c’ means that the dimension of variation is closed to the learner awareness. ‘o’ means that the dimension is opened to the learner awareness. Letters A, B, C, or D were assigned to the features, and numbers after that, means that there were sublevels within that feature. For example, participant 02’s awareness was closed to the Time as a Factor dimension of variation, and was opened and in the level A for the Systems / Models Usage dimension. Similarly, participant 13’s awareness was opened to the dimension Product tailoring in level B2.1, which means involving the stakeholders in the product development and make a solution for them. Finally, it is relevant to mention that the columns show the progression in which participants opened the dimensions of variation, and the rows the set of dimensions of variation that are included in each category of description.

		Systems modeling	Ecosystemicity	Syst Boundaries	Time as factor	Part-whole	Product Tailoring	Problem Rightnes	Power	Iterative Nature ProbSol
1	02-US01-03-En-F	oA	c	c	c	c	c	c	c	oA
	05-US03-01-En-F	oA	c	c	c	c	oA	c	c	c
3	21-US09-03-En-F	oB	oA	o1	c	c	oA	c	c	oA
4	19-US08-04-En-M	oA	oA	o2	oA	c	c	c	c	oA
5	22-US10-04-En-M	oB1/B2	oA	o1	oC	oA	c	c	c	c
	09-P04-GS01-En-F	oB2	oA	o3	oC	oA	c	c	c	c
	03-US02-03-En-F	oB1	oA	o1	oC	oA	c	c	c	c
	16-US07-01-En-M	o B.1/B.2	oA	c	oB	oB	c	oB	c	c
	23-P13-IP08-En-M	oB	oA	o1	oA	oA	c	c	c	oB2
	11-P06-EF01-Sp-M	oB1/B2	oA	o2	oC	oB	c	c	oA	oB2
6	18-P11-GS02-En-F	oB/B1	oA	o2	oC	oA	oA	c	c	c
	12-US06-03-En-F	oB1	oA	o3	oC	oA	oA	c	c	c
7	24-P14-IP09-sp-F	oA	oB	c	oC	oB	oB1	oB	c	c
	07-US05-03-En-M	oB	oA	o1	c	oA	oB1	oD	oA	c
8	20-P12-IP07-Sp-F	oB	oA	o1	oA	oB	c	oC	oB	c
	17-P10-EF03-En-F	o B.1/B.2	oB	o3	oC	oB	oB1.1	oA	oB	c
	06-US04-02-En-M	oB1/B2	oA	o1	oB	oA	oB1	oB	oB	c
	25-P15-IP10-sp-M	oB/B1	oA	o3	oB	oB	oB1.1	c	oB	c
9	04-P02-IP02-Sp-F	oB	oA	c	oA	oA	oA	oA	oA	oB2
	14-P08-IP06-En-M	oB1	oB	c	oB	oA	oB1.1	oB	oB	oB
	01-P01-IP01-En-M	oB1/B2	oA	o3	oB	oA	oB2	oB	oA	oB
	10-P05-IP04-En-F	oB1	oB	o1	oB	oA	oB2	oC	oA	oB
	15-P09-EF02-En-F	o B.1/B.2	oB	o1	oC	oB	oB2.1	oD	oB	oB1
	13-P07-IP05-En-M	oB1	oB	o3	oB	oB	oB2.1	oD	oB	oB1

Figure 4.6 – Outcome space or categories of description of addressing Complex Socio-Technical Systems

4.4 Conclusion

This chapter showed the nine critical aspects that a learner should learn to address problem sin engineering complex socio technical problems. These were identified because a variation was perceived in their understanding across all the participants in the sample, which is why these were called dimensions of variation. Also, an incremental awareness was proposed between them, based on the participants that were interviewed for this study. Nine categories of description were defined based on Marton's idea of opening one dimension at a time.

CHAPTER 5. DISCUSSION

5.1 Introduction

The results from this study are contributing to close the gap of knowledge regarding a descriptive developmental path for the ability to address complex socio-technical systems. I am proposing a path that was found following a blended phenomenographic approach that allowed me to answer the following research question: What are the various ways in which engineering undergraduate, graduate students, faculty, and practitioners address Socio-Technical Complex Systems?

You may recall that in section 2.7 variation theory of learning, I explained, based on Marton (2014), that a way a learner experiences an object of learning is described in terms of the critical aspects and critical features the learner is able to discern, and focus simultaneously, synchronically and asynchronically, while addressing an instance of that object of learning. Accordingly, for answering my research question, first, I found the critical aspects and critical features that describe what a given learner needs to learn to address complex socio-technical systems in an optimal way. You can find the set of nine critical features with its aspects in Table 5.1.

Second, I found a developmental path that is presented, using the phenomenographic language, as a set of categories of description that together describe an incremental level of awareness of the critical aspects needed to address complex socio-technical systems, going from a category in which a learner discerns only one critical aspect, to a category in which the learner discerns all the critical aspects, and focus on all of them simultaneously while addressing the task. You can find the nine categories of description in Table 5.2.

In the following sections you will find, first, a discussion on the critical aspects or dimensions of variation found; second, a discussion on the developmental learning of these critical aspects; third, implications for engineering education, fourth, a reflection and my recommendations on the methods, a set of interesting findings for future work, and the limitations of this study.

5.2 The critical aspects (or dimensions of variation) and features a learner needs to learn to address socio-technical systems

Results from this study suggest that there are nine critical aspects that a learner needs to learn to be effective addressing socio-technical systems which implies that a learner needs a mindset in which she allows these critical aspects to interact and constantly exchange.

Table 5.1 – Critical aspects and critical features that a learner needs to learn to address complex socio-technical systems

Critical Aspect (CA)	Critical features
CA1 - Systems / Models Usage	Closed to participant awareness • No use of models Opened to participant awareness • Users of model output developed by others • Using simple models (not considering variables simultaneously) • Using complex models (participant considers interaction of more than two variables simultaneously) • Model as a cognitive tool – Participants evaluate the current situation and compare it and contrast it with models previously learned
CA2 -Ecosystemicity Awareness	Closed to participant awareness • No awareness of other systems Opened to participant awareness • Stakeholders assumed, and in the learner awareness • Effort in identifying stakeholders in the ecosystem

CA3 - System's Boundaries	Closed to participant awareness
	• Boundary in simple systems (Technological systems). Hard goals.
	Opened to participant awareness
	• Participant's system boundaries are set
	  ○ to include the social component of the system
	  ○ to consider the system product lifecycle
	  ○ on customer's experience

CA4 - Time as a Factor	Closed to participant awareness • Sequential short-term cause and effect relationships Opened to participant awareness • Participant considers a longer span of time • Participant considers a longer span of time and is also aware of delays • Participant uses simulations to address the long term
CA5 - Part-Whole Relationships	Closed to participant awareness • Learner's attention focused on the parts Opened to participant awareness • They considered the relationship between the parts and the whole • They have a deeper understanding of how the details are connected with the behavior of the whole, and vice versa

CA6 - Effort in Product Tailoring	Closed to participant awareness
	• Learner is not aware of this need
	Opened to participant's awareness
	• They are aware of the need to tailor a solution
	• They identify the users,
	  ○ study the users and make a solution for them
	  ○ involve the users and make a solution with them
	• They identify all the stakeholders
	  ○ study the stakeholders and make a solution for them

Critical Aspect (CA)	Critical features
	o involve them and make a solution with their representatives
CA7 - Problem Rightness (Related to Problem Definition)	Closed to participant awareness • Participant jumps into a search of a solution assuming the problem is right Opened to participant's awareness • Participant believes the task is not a real problem and owner of the task knows what the problem is. • Participant seeks for the current system in place and identifies possible flaws that can be addressed to make it better. • Participant seeks for the big picture
CA8 - Power Relationships when working with others and for others	Closed to participant awareness • When participant engaged in hierarchical power relationships with others Opened to participant's awareness • the participant engaged in pluralistic (interactive) Power Relationships • the participant engaged in participative power relationships
CA9 - Iterative nature of problem-solving	Closed to participant awareness • when they did not iterate or talked about it. Opened to participant's awareness • participant iterated with themselves. They seek for feedback at a personal level (metacognition) • sought for ways to measure the system's performance. • Participant

5.2.1 The interactions between the critical aspects

The results from this study suggest that the critical aspects are not separated in the learner's mind when addressing a socio-technical system, but that they co-exist and interact with each other; especially after the learner reaches a higher awareness of the features of each dimension of variation.

For showing this interconnection between the critical aspects I will show first how two different participants thought about one of the critical aspects, and later, how the most advance participant interconnected this aspect with other aspects. The two participants chosen for this example are participant 05, a female First Year Engineering Student in the lowest part of the developmental path for the ability under investigation in this study, and participant 13, a male industry practitioner with more than 20 years of experience, who is in the category of description 9, the most advanced in the developmental path. The aspect we will compare is Effort in Product Tailoring.

When addressing the task 1, Participant 05 thought about a solution from what she believed was right to have in an emergency response system, but she did not think about tailoring the solution according to the customers' needs. Participant 13, on the contrary, not only thought about the stakeholder's needs but also thought about involving them in the team to reach a solution that satisfies the different stakeholders. Beyond this, he shows awareness of what could it be if the solution is not tailored. During the interview, he said that he and his team can come out with recommendations for the system for tornadoes, but not necessarily the stakeholders will agree or do not like the recommendations for the system. Here he shows that he is aware of what the impact could be if the tailoring aspect is not taken into account. He also discussed the need of including the stakeholders in the team to tailor the system according to the stakeholders' needs, which would make the stakeholders buy in and accept the recommendations for the system.

The comparison between participants 05 and 13 shows that participant 13 might be more effective than participant 05 when addressing the complex socio-technical systems especially because his recommendations for the solution will be accepted by the stakeholders. Participant 05's system might not be accepted or used by the stakeholders because, if we follow the logic proposed by participant 13, the stakeholders were not involved in the solution process.

In addition, the interview from participant 13 also shows that while he is focused on a critical aspect, such as [1] Product Tailoring, he is also focused on the other critical aspects as well, which allows him to address the task effectively. For example, participant 13 was also focused on identifying the people who would be affected by the system, moving the System's Boundaries [2] to include the social component of the system to make the system acceptable. He was also focused on the [3] Power Relations critical aspect because when he discussed the need to tailor the product, he thought that it was necessary to involve the stakeholders in the process, and in creating a code of cooperation within the members of the team to make sure that the team will work together, and would have a way to manage possible issues that might arise with the team in the long term, showing that he also considers the [4] Time as a Factor. When thinking in tailoring the solution, he was also focused on the Ecosystem, and that is why, he said, he would recruit in the team different stakeholders, such as "parties responsible for executing the process, for example, emergency response: ambulance, security, … decision makers: Mayor, Police, Chief, and representatives of the people affected". Thinking of all of these parties shows [5] Ecosystemicity, and thinking about understanding "the entire response process" and how these parties contribute to the whole shows awareness of [6] Part-Whole relationships, these also connected with Product Tailoring. Being willing to involve the stakeholders in the process, shows again his simultaneous focus on the Power Relationships critical aspects. This participant also did not immediately start seeking for solutions, but stated that it was relevant for him to "get a clear understanding of what the problem is, and what people want out of it, and to get the stakeholders included in the problem definition and resolution process". This is an evidence of focusing also in [7]

Problem Rightness, because he would look for having a clear statement of what the right problem is, to tailor a right solution.

In the paragraph above, I showed you that the participant was focused on 7 different aspects simultaneously when addressing the complex socio-technical system, and evidence showed that he could also be aware of the other two if it is needed. For example, awareness of iteration in the first task is evident when he said that he would first have a small team, and later he would increase the number of people in the team based on the new complexity that needs to be managed in the system [8]. Complementary, the use of models was not explicitly discussed in task 1 by this participant, still, he was aware of them in task 2 [9].

The example above shows that this participant, when addressing the complex socio-technical system in task 1, considered the critical aspects he thought were needed simultaneously. This awareness of what is needed to consider suggests that students need learning environments in which they get aware of what it is needed when addressing a socio-technical system, especially what could happen if these critical aspects are not considered when designing a solution. I will be back to this idea in the teaching implications section.

5.2.2 Critical aspects and the engineering problems

The results from this study in regards to the critical aspects that a learner needs to take into account when addressing complex socio-technical systems respond adequately to the characteristics described in the literature for engineering problems and complex problems. For example, Funke (1991) proposes that a complex problem is "intransparent", meaning that "only some variables lend themselves to direct observation", and Koen (2003) that a complex problem has uncertainty. These two characteristics, uncertainty, and intransparency were tackled in task 1 by, for example, participant 15, a female faculty engineer with more than 20 years of experience, by doing "leg work", asking questions such as "what is exactly wanted, who is funding it, … I would want to know the time frame…" These questions are evidence of being focused on critical aspects such as Problem Rightness (what is exactly wanted), and Ecosystemicity (who is funding it), and Time as a Factor (time frame).

Another characteristic of engineering problems is that they cause a transition from a state A to a state B that is better, must abide a set of constraints and have limited resources (Koen, 2003). Participant 15 was aware of the need to identify state A, and wondered what infrastructure was already in place in Indiana, and how people currently respond to tornadoes, which is a crucial feature of the Problem Rightness critical aspect. Additionally, the participant was also concerned about the resources because she asked who would fund it, and if she would have all the resources she needed to address the problem, which is part of the Problem Rightness critical aspect as well. It is relevant to mention that other aspects could be also involved. For example, the participant 15 also said: "I would want to understand the impacts to the community … I'd get the community involved as well, so they can sort of buy into the solution". The fact that she wanted to know the impact on the community, shows that she shifted her system's boundary to include the social component. Similarly, discussing involving the community in the problem definition and solution processes shows her awareness of the Power Relationships critical aspect.

Other characteristics of complex problems are "Polytely" or the multiple goals in the members of the system, complexity of the situation and time delayed effects (Funke, 2001). Evidence from participants who opened all the critical aspects shows that participants focused on the critical aspects to address these characteristics. For example, dealing with the time delayed effects was achieved when the participant focused on the Time as a Factor critical aspect.

Similarly, for dealing with the Polytely, participant 13 made his team to agree on the problem definition statement. This ability to manage the different people's goals, expectations and perspectives of the system through meetings and interaction requires to focus on the aspect Power Relationships.

The need of being aware and focusing on the Power Relationships critical aspect can also be inferred from Bucciarelli's proposal of design as a social process (2003), and from the Human Centered Design domain. In Bucciarelli's proposal, there is a team that (Bucciarelli, 2003, p. 9):

> must work together to create, imagine, conjecture, propose, deduce, analyze, test, and develop a new product in accord with certain requirements and goals … while they all share a common goal at some level, at another level their interests will conflict. As a result, negotiation and "trade-offs" are required to bring their efforts into coherence.

Overcoming hierarchical power structures in a team will allow the members to agree on the goals and work together to reach them, as it was proposed by participant 13, instead of having members working in isolation addressing disciplinary issues as it was found in several transcripts (e.g. Undergraduate students: 02, 05; Graduate students: 09; and professionals: 23).

Unlike the design as a social process, focused on making the team work effectively, the Human Centered Design is focused on the customer/stakeholders satisfaction. Designers with high levels of Human Centered Design established collaborative and participative relationships with their customers/stakeholders (Zoltowski et al, 2012). Results from this study suggest that for establishing collaborative relationships with the customers/stakeholders it is necessary to be aware of the Power Relationships aspect. This is because participants who were aware of the critical aspect Power Relationships, showed that they would involve the user/stakeholder in the problem definition (Problem Rightness aspect), and in the development of a solution (Product Tailoring). For example, participant 25 in task 2 was concerned about the workers and suggested ways in which they can communicate with people from the sales department to diminish the issues between them. This shows awareness of the critical aspect Power Relationships, and that awareness allows him to deal with the conflicts between the different teams in an organization.

The evidence collected in this study suggests that by learning the critical aspects that were found in this study a learner might be better prepared to address effectively a socio-technical system.

5.2.3 Critical aspects in knowledge domains

The critical aspects found in this study are consistent with three different knowledge domains that can be found in the literature: Systems Thinking, Design Thinking, and Management. The critical aspects Systems / Models Usage, Ecosystemicity, System's Boundaries, Time as a Factor, and Part-Whole Relationships are connected with the literature on the Systems Thinking domain. Effort in Product Tailoring, Problem Rightness, and Iterative Nature of Problem Solving are also consistent with the literature on Design. Finally, Power Relationships is linked with the literature in the management domain, specifically the one in the Systems Management one.

These connections of my findings with literature in several domains suggest that a learner, to be effective addressing complex socio-technical systems, needs training in systems theory, design thinking and practice, and management. This integration was achieved by experts who participated in this study while they were dealing with the task.

Two disciplines that may integrate these knowledge domains are Systems Engineering and Systemic Design. Systems Engineering is defined as (SEBoK, 2016):

> An interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.

It also proposes that "solving complex problems needs to combine elements of systems theories and systems approaches to practice" (SEBoK, 2016).

The critical aspects found in this study resonate with the two statements on systems engineering just cited. The systems thinking domain knowledge might be related to the systems theories element, and the aspects in the design knowledge domain might represent the approaches to practice. In fact, the activities mentioned in the definition presented above resonate with those found in my study.

Pertaining to the Systemic Design discipline, it proposes that for addressing complex social systems, it is needed to combine systems thinking and design thinking

(Jones, 2014). In this regard, Jones proposes that although design thinking is powerful for "aligning organized action with a social goal," but it might not be good enough for meeting "the scope and magnitude of the social and systemic issues facing humanity and society today". The author continues later stating that "without a significant basis for theoretical support, such as systems theory, design thinking is at risk of becoming a management fad" (Jones, 2014, p. 123). My findings are consistent with this idea and are suggesting, as stated before, that systemic design thinkers require management skills to be able to work with others.

Table 5.2 – Categories of description or different ways of experiencing addressing complex socio-technical systems

Category of Description (CD)	**Critical Aspects**
CD1: Model Interpreter	Opened by participants in this category Systems / Models Usage
CD2: Recognizing complexity	Opened by participants in this category Ecosystemicity Awareness Already in participants' awareness Systems / Models Usage
CD3: Recognizing different boundaries	Opened by participants in this category System's Boundaries Already in participants' awareness Ecosystemicity Awareness, Systems / Models Usage
CD4: Recognizing time as a factor	Opened by participants in this category Time as a Factor Already in participants' awareness System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage
CD5: Recognizing wholes	Opened by participants in this category Part-Whole relationships Already in participants' awareness Time as a factor, System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage
CD6: Recognizing the need of tailoring	Opened by participants in this category Effort in Product Tailoring, Already in participants' awareness Part-Whole relationships, Time as a factor, System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage

Category of Description (CD)	Critical Aspects
CD7: Recognizing the need for identifying the right problem	<u>Opened by participants in this category</u> Problem Rightness <u>Already in participants' awareness</u> Effort in Product Tailoring, Part-Whole relationships, Time as a factor, System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage.
CD8: Giving voice to others	<u>Opened by participants in this category</u> Understanding of Power Relationships when working with others and for others <u>Already in participants' awareness</u> Problem Rightness, Effort in Product Tailoring, Part-Whole relationships, Time as a factor, System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage
CD9: Embracing continuous improvement	<u>Opened by participants in this category</u> Iterative Nature of Problem Solving <u>Already in participants' awareness</u> Problem Rightness, Effort in Product Tailoring, Part-Whole relationships, Time as a factor, System's Boundaries, Ecosystemicity Awareness, Systems / Models Usage

5.3 The learning of the critical aspects: The Categories of Description

Learning, as it was presented in chapter 2 using Marton's variation theory as conceptual framework, has 4 different patterns: "repetition", that happens when the learner has not opened a dimension of variation to her awareness, "contrast", meaning that the learner gets aware of a new critical aspect, or in other words, opens a new dimension of variation; "generalization", in which the learner learns that there are different features or values within the dimension; and 'fusion', in which the learner experience all the critical aspects or dimensions of variation she discerns of the object of learning "simultaneously after having separated them."

As I said before, the categories of description describe an incremental level of awareness of the critical aspects that are needed to address complex socio-technical systems. Since there are nine critical aspects, addressing socio-technical systems could be experienced in nine qualitative different ways.

Results from this study suggest that the learning of the critical aspects for addressing complex socio-technical systems, develops incrementally from the aspects that are related to the systems thinking knowledge (Systems / Models Usage, Ecosytemicity awareness, System's Boundaries, Time as a Factor, and Part-Whole relationships), to those related to the design thinking domain (Effort in Product Tailoring, Problem Rightness), to the one related to management (Power Relationships) and finally another one that might interconnect the three and (Iterative Nature of Problem Solving).

Results also suggest that opening a new dimension allows the learner to learn more advanced features in dimensions of variation already opened.

For example, the data shows that participants who opened the Problem Rightness dimension of variation were tailoring the system from a more advance feature, than those in which Problem Rightness was still closed to their awareness. This relation between a dimension of variation that is just opened and those already opened implies that the developmental path for this ability goes in different directions. In one direction the learning path can be described as opening a new dimension of variation; in another direction the learning path might be described as going backwards, which means that once a new dimension of variation is opened, new more advance features or new connections between the dimensions can be learned by the learner.

5.4 Implications for Engineering Education

Two key findings that have crucial implications for engineering education were stated in the previous sections. The first one is related to the learning environments that could be more effective to facilitate student's opening of the dimensions, and the second one suggest an order in which these dimensions are likely to be opened by learners.

5.4.1 The learning environments

Opening a dimension of variation in the learner awareness requires contrast. According to variation theory, this contrast is achieved by experiencing the difference of one dimension of variation against a background of sameness (Marton, 2014). As it was stated in the first section, to be able to learn the nine critical aspects students need a safe learning environment in which they can experience the variation of the critical aspects found in this study, but one at a time. This implies that learning environments in which students could be exposed to a real or a simulated (with instructors playing roles) socio-technical problem for a longer span of time.

One example that might be related with this implication is the Engineering Projects in Community Service – EPICS. This program has shown that it is a good strategy to develop systems thinking in college education, especially because it provides a "safe place to explore how to solve complex and real problems" (Huff, Zoltowski, & Oakes, 2016, p. 66). One of the possible reasons that could explain why it works as a teaching strategy to develop systems thinking is that students who spend several semesters there usually take different roles and see the same problem from different perspectives. This interaction with the problem, and with their instructors, who might help them to get aware of the dimensions of variation, might support student's opening of one or more dimensions of variation, or the learning of a new value within a dimension already opened.

Another teaching strategy in which the learner deals with the same problem several times from different perspectives is called productive failure (Kapur, 2010). In this teaching strategy the instructor design problems that cannot be solved, even if the learner considers different alternative paths to find a solution. According to Kapur, the interaction with the various aspects of the problem makes the learners better at addressing those kinds of problems.

These two examples of teaching strategies lead to a question in respect to the the span of time, and the kind of experiences that a learner needs to open the nine critical dimension of variation found in this study.

5.4.2 Implications for curriculum designers

The findings from this study are suggesting a developmental path for the learning of the nine critical aspects a learner needs to learn to address complex socio-technical systems. The study suggests that the developmental path goes in two directions. In the first one, it goes forward, increasing the number of critical aspects or dimensions of variation that are in the learner awareness. In the second one, it goes backwards, supporting the learning or more advance features within dimensions of variation already opened.

In the first developmental path, systems thinking related knowledge is opened first in the learner awareness. This implies that engineering curriculums may support better students' learning of engineering design if they promote the development of systems thinking in the first years of the program.

The second developmental path implies that curriculum designers might get better student outcomes if students have time to either go back and work on the same problem with a new light provided by their awareness of a new dimension of variation, or at least, time to reflect upon what they did in situations in which awareness of a critical aspect was needed to address it in a more powerful way, and what would they do now.

In addition, the findings also imply that a strategy must be followed to support student's opening of the Power Relationships dimension of variation. This is because participants who had this dimension opened reached higher features in other dimensions such as Problem Rightness and Product Tailoring. This is because, by opening this dimension, participants work better with people, and have a higher appreciation of their possible disciplinary contribution. This is consistent with the Human-Centered Design literature in which the highest level of it, "empathic design", is reached only when people users are seeing as equals (Zoltowski, Oakes, & Cardella, 2012; Zoltowski, 2010).

Finally, regarding the System's Boundaries dimension, in this study, I found variation in the boundaries that participants set when addressing the complex socio-technical system. However, there was not a pattern that implies that by opening certain others more advance dimensions of variation, a higher or more complex feature would be reached. This implies that we, as educators, should guide students not only in the opening of the system boundary dimension but also in reaching its advance features. This is because, this study suggest that a learner can progress in other different dimensions, but still get fixed on this one, making them missing in part the complexity of the socio-technical system, that might lead to a project failure.

5.4.3 Implications for assessment

The Variation Theory, and the approach followed in the second stage of this study, assessing participant's transcripts using as coding scheme the dimensions of variation and its features, suggest that student's learning might be better assessed if they are evaluated at different moments of time using the same task. This is because the instructor will better see the variation in the opening of the critical aspects in the learner awareness if the learner addresses the same problem.

Additionally, although this study used two tasks, it might be better to design a single task in which all the nine critical aspects are necessary for addressing the complex socio-technical system in it effectively. This is because of the limitations of time and resources we have in the academy and is especially necessary for courses in courses with a large number of students.

Finally, since the interest is in regards to the learning to address complex socio-technical systems, an oral assessment asking what the student would do to address that socio-technical system might provide a better understanding of students' learning than written one. This is because the instructor can ask probe questions that clarify the student's current level, which is similar to what I did during the interviews, only that this time the instructor will know where a deeper understanding is needed; and the students can express better their understanding of the connections and interaction between the system they would design, and the ecosystem that surrounds it.

5.5 Reflection and recommendations on the methods

Using the blended approached allowed me to find nine dimensions of variation that are critical for addressing socio-technical systems. The approached I used as a framework for my data collection allowed me to experience the variation in what the participants thought it was necessary for addressing the tasks, and allowed me to identify several dimensions of variation that are interconnected.

The results from this study suggest that for data collection it is better to use two or more tasks instead of one. This is because, in my study, task 1 was better for making visible participants' practices in the design of systems, while the task 2 was better for making visible participant's understanding of systems concepts. This was noticed when I was analyzing the data. There I found that sometimes participants in task 2 did not talk about product tailoring, but they did in task 1; or on the contrary, they talked about the delay effects in task 2, but they did not in task 1.

I would also recommend that the researcher gets prepared for data collection. In my case [1] I was interviewed by another phenomenographers who was finishing her Ph.D. in Engineering Education at Purdue. I was also interviewed by one of my co-advisors using one of the tasks I tested in the preliminary stages. Finally, I conducted pilot interviews and had my co-advisors to listen to a portion of one of the interviews I did, where they could give me feedback. All this preparation was key for succeeding in the interviews because each of them is too valuable and cannot be repeated.

5.6 Interesting findings for further work

5.6.1 Documentation

One interesting finding that maybe necessary to explore further is that industry participants number 14, 10 and 3, talked about documenting. Unfortunately, the data was not enough for describing variation in this area, and it was not selected as a critical aspect. However, documenting might allow addressing complexity in a more powerful way because allows keeping the history of the project, allows a better communication between sub-systems in a synchronic and an asynchronic way, and facilitates the understanding of different perspectives proposed by people that can be studied before a meeting. More information in this regard would be necessary to validate the limited literature (Logan, Harvey, & Spencer, 2012; Long 2015) that connects documenting, modeling, problem solving, complexity and socio-technical systems and how documenting supports the ability to address complex socio-technical systems.

5.6.2 Awareness of interdisciplinary work

Another topic that was interesting was that there was some variation in the disciplines participants could consider. In task 1, participants with lower levels of awareness thought about teammates with experiential knowledge, so they asked for people from “flat land”, or people who have experienced tornadoes. Later, people with higher level of awareness of what is needed to address complex socio-technical systems were able to identify specific disciplines that they thought were needed to address the problem. This awareness of interdisciplinary work is interesting because, although task 1 specifically asked participants to think about expertise from other disciplines, these disciplines were not recognized by learners with a lower level of awareness. This finding is consistent with the results offered by Hsu (2015). She found in her dissertation study seven different categories of description in which students' experiences of interdisciplinary learning go from no awareness of differences to an appreciation of the contribution of other disciplines for addressing the problem more effectively. The results from this study suggest that these high levels of recognition and appreciation of other disciplines are reached after the participant gets aware of the Power Relationships critical aspect, and the participants in the highest category of description discussed the need to recruit in the team people from other disciplines as crucial for addressing the complexity of the problem.

5.6.3 Transfer of the critical aspects to a different problem

Finally, I will present another interesting finding regarding three different kinds of problems proposed by participants when they were asked to think about similar problems for task 1 and task 2. In the first kind of similar problems proposed by some of my participants, in lower categories of description, they proposed problems with similar surface features to the original ones. For example, participant 02 proposed another conference but in this case of teachers.

> 02-US14-01-En-F So I have to create a problem similar to this, oh, probably maybe something with exams or just say teaching techniques or like education systems, so is instead of conference of predicting national disaster, it would be like international conference of like teachers or something like that, and then, you have teachers from all around of the world, and then, at the end of the conference you will bring together a team of teachers that will help on developing new ideas for teaching students how to, learn a certain topic …

As you see, participant 02 though about another conference in which a topic can be in a way comparable to the design task or problem 1 I gave her.

In the second type of the "finding similar problems answers", participants in middle and high levels of categories of description proposed a similar problem based on a number of components, disciplines, people and relationships that are part of the system they perceived in their awareness. The following quote from participant 06 exemplifies this:

> John: So why is it similar to the problem in task 1?
>
> 06-US09-04-En-M: It has very different components that all need to be integrated in order for it to work properly, or to work in an ideal situation, and to meet that end goal that I hope we can achieve

As you can see, this participant thought about components that need to be integrated which denotes a different way to understand the problem in task 1, and its possible solution.

In the third way to think about similar problems, they proposed that the similarities between the problems rely on the behavior of the system across time. The following quote from participant 15 exemplifies this:

> 15-P09-EF02-F: Okay. So, in other words, it would have to be a system that was designed, this particular system has to be ... Is it going to be dormant for a long period of time, and then all of a sudden it's going to need to function flawlessly for a very specific time period. So, you know, I could even think of shooting the Mars Rovers at Mars. Basically, you know the shot, the Mars Rover and this big, sort of, balloon like thing. It ... They had to shoot it so it would hit Mars at the right time of its orbit. But basically it's remained dormant the whole time then all of a sudden it had to deploy. And weigh in the Rover just for a period of a very short period of time. Five minutes. You know? It bounced around on the planet and then it had to open up. And then once the Rover got deployed, it was done. It ... You know, that use of that system wasn't needed anymore until the next time they shot a Rover at the ... At Mars. Basically.

In the previous quote, you can see that the participant discusses the similarities in relation to behavior when she expresses that the system must remain dormant for a long time, and work flawlessly when it is needed. Since the participants with higher expertise were the ones who proposed alternative problems such as the one in the third proposal, further study should be performed to determine the interconnection of the opening of critical aspects with the change in perspective.

5.7 Limitations of the study

The study had several limitations. [1] Participants were asked to respond to a task that was not relevant to them. This limitation is related to the possible motivation that participants may have had for addressing the task using all their cognitive. In fact, at least two participants said that their thought was: let's finish as soon as possible.

[2] In the first task, the disaster response system, the original task is asking directly for issues and people from other disciplines in the team. I believe that was a limitation of the first task because you are asking to the participant directly to consider different disciplines needed for solving the problem. I believe a better question would be to ask the participants what they would do if they were asked to design a disaster response system for tornadoes in Tippecanoe County. In that way, maybe the participant would choose if she would recruit other people and from which disciplines, or if she would work alone. That might allow a future researcher to explore and maybe find other dimensions of variation that were not identified in this study.

[3] There is no certainty about the number of critical aspects needed to address complex socio technical systems. The tasks chosen may have failed to make visible other critical aspects that are only visible with a different task.

Another limitation in my study is that, even though I tried to make it multi-racial and worldwide, most of my participants were white and born in the United States: 52% (13/25participants) were white, whereas the 28% (6/25 participants) were Latino, 8% (2/25) were Asian, 2% (1/25) was from Africa, and another 2% was African American. Similarly, 50% of the sample were born and raised in North America, 2% were from Europe, 24% was from South America, and 2% (1/25) was from Africa.

The study is also limited to the disciplines that participated in it. I have engineers from several disciplines, but I also would have liked to include in my participant ecological, environmental or agricultural engineering participants, especially professionals, who can bring their insight. Having participants from this areas would increase the chances of having covered all the different dimensions needed to address complex socio-technical systems. Still, the current set found in this study is good enough to explain the developmental path.

Another limitation is that the interviews and the data analysis were done only by me, which makes the results of the study be seen only by my eyes. It means that the results were created based on the awareness I have and I have learned from this study, of what the complexity of a socio-technical system currently means for me. That awareness helped me to filter information I considered relevant from that one that I considered non-relevant. There is a chance that with a higher future awareness of the topic, I get a new interpretation of the variation in some dimensions, or find new ones.

Finally, the hierarchy defined based on the whole transcript makes the hierarchical results dependent on the participant's performance, which is a limitation since we cannot assume that all the participants took the task seriously and did their best as they might do in a real world situation.

CHAPTER 6. RECOMMENDATIONS AND FURTHER WORK

In this chapter, you will find the recommendations and the future work that may follow this dissertation. The recommendations are based on the lessons I learned, and I believe I would have liked that someone would have given me some of them. These recommendations are targeting qualitative researchers, phenomenographers, faculty using the results of my work, and assessment developers. Complementary, the future work referenced here was found in different stages of my dissertation, but specially during the data analysis, and while writing this document.

6.1 Recommendations

6.1.1 For qualitative researchers

As I stated at the end of the previous chapter, it was good for me to devote time for calibration of myself as a qualitative researcher conducting interviews for data collection. This was because interviewing requires several soft skills, especially learning how to engage with others in dialogic conversations that allow participants feel in a trustful environment in which they can freely express their inner thoughts. In regards to logistics, I would say that if you are doing skype or phone interviews, ask your participant, if possible, to record from their side and send you the audio file later. Unfortunately, sometimes it looks like the audio-recording is clear while you are doing the interview, but the audio most of the times, at least in my case, was not clear enough to facilitate a fast transcription process.

Finally, I would encourage you to not be afraid of the data, especially because the only way to understand it is by being submerged in it.

6.1.2 For phenomenographers

The first recommendation I will give you is that I have found that using a common background to perceive the variation among the different participants has several advantages. The first one is that it provides you with a controlled environment in which you can dig easier into participant's meaning. What happened to me when I tried the other approach, there was an expression used by Ackerlind, who said that during the interview, there was a moment in which she clicks and realizes the meaning of the experience for that particular participant. That click moment did not happen to me while I was conducting my pilot interviews with that approach. On the contrary, the second method, using a task, allows you to perceive the variation among the responses provided by participants, as well as the differences in meaning when they talk about the same thing.

Regarding my interview, I used two different tasks in which I asked the participant to tell me after each of those the meaning of what they did. After completing that part of the interview, I asked them to think about similar problems for each task (which I called transfer problems) and to compare and contrast them. I recommend being sure that you have time to explore these answers with the participant because they could reveal in great proportion the degree of openness of the dimensions the participant has, and the aspects of the problem in which they focused their attention. Similarly, when they look for similitudes and differences between two tasks, they use their deeper understanding of the tasks to think about these similarities and differences. It happened to me that few participants found the two tasks completely different, those incidentally were in the group of participants with all the dimensions opened.

Regarding data analysis, I suggest to study the transcripts of each task separatedly and include the transfer problems in your reading. Later, you will see dimensions of variation that overlap, and others that do not, but that could be critical for a more efficient way to address the problems in which you want to develop students' ability to address.

Another recommendation is related to the expression that says that meanings will emerge from the data. My advice in this regards is simple, just be patient, and read first all the transcripts, and choose a subset of those that look very different in terms of awareness. Then read those several times before doing anything else. With the time, you will start seeing the different features in a dimension.

6.1.3 For faculty using my results

The framework developed as result of my dissertation can be used as an informal guide to determine students' current awareness of how to address complex socio-technical systems. The first one is that faculty should design curriculum interventions aiming to open one dimension of variation at a time. That, according to Marton, can be achieved by offering students contrasting cases (Marton, 2006).

The teaching technique of contrasting cases was developed using as framework Variation Theory, which as I have stated several times in this document, proposes that people learn if they opened a new dimension of variation, or learn a new feature or value within a dimension. Contrasting cases are especially powerful for facilitating the opening of new dimensions of variation.

Here I propose an example on how to create an instructional intervention for opening one of the dimensions. Still, it is necessary to test its effectiveness. An educator who wants to facilitate the opening of a dimension, let's say Time as a Factor, could ask her students to consider different factors for making an informed decision. The key would be that the effect of the decision will be perceived only after a span of time. For example, in task 2, ask them to make decisions on inventory without considering the time delay. Once they make the decision, ask them to try again, or show them a more powerful technique that is accomplished by considering, in this case, the time delay. Yet, remember to keep everything else the same. In this case, students will be able to notice what changed because you kept the same background. This strategy might facilitate the learners' opening of a new dimension, in this case, the time as a factor. Once the learner has opened the dimension, the instructor should facilitate, again, by contrast, the learning of different features. In our example with the Time as a Factor dimension, showing more examples of not considering the delay vs. considering it, and observing other ways to play or consider the variable time as a factor in the understanding of complexity within the system. The whole idea is that the learner gets confident with the variation within the dimension, this is called by Marton "generalization". Once they learn different values within the dimension, the instructor should guide the student to understand what happened with the other dimensions already opened when time takes different values. This is called by Marton "Fusion".

In addition, I want to remind you that this outcome space is not a checklist that students should learn by heart. What this is, is a tool for you as an instructor to know how much you should work on helping students to appropriate each of those critical aspects of their own practice. This also means that you will need students to be exposed to real world problems or at least real-world simulated problems in which they can experience the complexity of socio-technical systems, and your role will be to help them to address the problem by opening one dimension of variation at a time, following the hierarchical structure I developed in this study.

Finally, following Marton's recommendations in regards of Variation Theory, I would recommend that educators assess students' learning using the same task at different moments. This is because keeping a background of sameness allows perceiving the variation in this case, of a new dimension needed to address complex socio-technical systems.

6.2 Further work

In the discussion section, I mentioned these possible directions for future work:

- Making formal the different outcomes from sub-processes within the system was relevant for some engineering practitioners who incidentally were systems engineers. For example, some talked about writing the problem statement and making sure everybody involved in the project agree (P13), or define the system's requirements with the stakeholders and make sure there is a document they can go back to recall what was said (P10), or having documents as communication vehicles between different teams involved in the system design (P14). I believe it might be relevant to study if documentation is another dimension of variation, or instead is a tool that engineers used and what is their purpose.

- Since there might be a relation between the span of time in which a learner is involved in a project addressing a complex socio-technical system, and the opening of the critical dimensions found in this study that are necessary to address it in a powerful way, considering what happen during that time with students awareness of what is needed to address complex socio-technical problems might be an interesting resource for curriculum developers.

There are also other possible research directions that emerge from this study:

- First, the outcome space can be used as the foundational framework required for developing an assessment tool that will allow an instructor to assess their student's ability to address socio-technical systems. The question we could ask from here is: How can we use the outcome space to create the assessment tool that could be used widely by educators, and how could this assessment tool be used to evaluate current curricula intended to develop engineering skills related to systems thinking?
- Since the outcome space could be used as the basis for an evaluation tool for assessing the ability to address socio-technical systems, a further validation of these results should be prioritized if we want this tool to be adopted widely by faculty and industry practitioners.
- Regarding the effectiveness of curricular interventions that could facilitate the opening of dimensions of variation, we a further research topic can be guided by

> the question “what are those learning experiences that we can bring to the classroom that promotes the opening of specific dimensions of variation, and how can we assess its effectiveness?”

Since one way a learner learns is by learning new values within a dimension of variation, it is crucial to study critical dimensions individually, and find a developmental path for each of them. There is some work already done in this regard, especially in the context of design. For example Zoltowski’s dissertation (2010)inform in more detail the development and interaction of two of the dimensions, product tailoring, and power relationships. There is a need to understand deeply the variation in each dimension and the interaction with other dimensions to facilitate student’s learning process of generalization and fusion proposed by variation theory.

CHAPTER 7. CONCLUSIONS

In this study, I found nine critical aspects and a number of significant features within each of those aspects that are needed for addressing complex socio-technical systems in a powerful way. A developmental path describing a hierarchical structure of awareness of these critical aspects is also offered.

These results were found using as research approach a blended phenomenography. For data collection and data analysis regarding the finding of the dimensions of variation, I followed Marton's approach, and for finding a hierarchical structure between the dimensions of variation, I used the Australian (developmental) approach. Marton's approach proposes for data collection where the participants experience the same instance of the object of learning (in this case, the participants all experienced the same two tasks). This case works as, in terms of Variation Theory, a background of sameness. I, as a researcher, experienced the variation of responses against that background, which allowed me to identify features that were varying across the same context. Those features together allowed me to define a dimension of variation. I conducted this process for nine different dimensions of variation I found.

The incremental awareness of the critical aspects a learner could experience is defined as dimensions that are opened in the learner awareness.

The phenomenographic developmental approach (Australian) was applied to find the hierarchical structure. The process I followed to build this hierarchy was: I assessed the participants' performance in regards to the dimensions of variation they opened during the interview and the different features they showed (in other words, seek for evidence in the transcript in regards of expressions that shows awareness of dimensions). After this, the participants were arranged from the participant who during the interviewed opened fewer dimensions, to the ones who opened all of them.

The critical aspects for addressing a problem in a complex socio-technical system, ordered in hierarchical awareness, are Systems / Models Usage, Ecosystemicity Awareness, System's Boundaries, Time As a Factor, Part-Whole Relationships, Product Tailoring, Problem Rightness, Power Relationships, and Iterative Nature of Problem Solving.

The categories of description were defined based on combinations of the different dimensions opened in the learner awareness, having one dimension opened at a time. A category of description describes how a learner at certain moment of time is aware of critical aspects and features for addressing the complex socio-technical system. Finding as much as possible of these categories of description is key for understanding students and helping them in their learning process. Additionally, these categories allow assessment designers to build upon an assessment tool that can be used across different engineering programs for developing evidence of effectiveness in regards of the development of systemic design thinking, or the ability to address complex socio-technical systems.

In conversations with colleagues who were using phenomenography as research approach, one of the concerns we all have is the feeling of being overwhelm by data, and not knowing how to make sense of it. I would argue that by using variation theory as a conceptual framework, this anxiety is mitigated because it is easier for the researcher to detect and define the variation in similar "things", that at the end would be defined as dimensions of variation. Still, the data analysis took me apparently a longer time than the time it took to my colleagues to work in their phenomenographic studies.

Regarding the structure of the outcome space, it shows that the progression of a learner's awareness goes from being model-focused, to a moment in which she gets aware of what is needed to address complex socio-technical systems, meaning that the learner will explore that beyond data, predictive models, and historical information, and would seek to understand the context, and would recognize that she cannot be aware of all the complexity by herself, and she needs to work with others. Finally, she would engage in iterative processes that would allow her to improve her solutions, while learning more about the problem.

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APPENDICES

Appendix A IRB Human Subjects Approval

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	MONICA CARDELLA WANG 4543
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	11/25/2014
Committee Action:	**Approval**
IRB Action Date	11/24/2014
IRB Protocol #	1409015196
Study Title	Identifying variation in ways to deal with problems in complex systems
Expiration Date	11/23/2015

Following review by the Institutional Review Board (IRB), the above-referenced protocol has been approved. This approval permits you to recruit subjects up to the number indicated on the application form and to conduct the research as it is approved. The IRB-stamped and dated consent, assent, and/or information form(s) approved for this protocol are enclosed. Please make copies from these document(s) both for subjects to sign should they choose to enroll in your study and for subjects to keep for their records. Information forms should not be signed. Researchers should keep all consent/assent forms for a period no less than three (3) years following closure of the protocol.

Revisions/Amendments: If you wish to change any aspect of this study, please submit the requested changes to the IRB using the appropriate form. IRB approval must be obtained before implementing any changes unless the change is to remove an immediate hazard to subjects in which case the IRB should be immediately informed following the change.

Continuing Review: It is the Principal Investigator's responsibility to obtain continuing review and approval for this protocol prior to the expiration date noted above. Please allow sufficient time for continued review and approval. No research activity of any sort may continue beyond the expiration date. Failure to receive approval for continuation before the expiration date will result in the approval's expiration on the expiration date. Data collected following the expiration date is unapproved research and cannot be used for research purposes including reporting or publishing as research data.

Unanticipated Problems/Adverse Events: Researchers must report unanticipated problems and/or adverse events to the IRB. If the problem/adverse event is serious, or is expected but occurs with unexpected severity or frequency, or the problem/even is unanticipated, it must be reported to the IRB within 48 hours of learning of the event and a written report submitted within five (5) business days. All other problems/events should be reported at the time of Continuing Review.

We wish you good luck with your work. Please retain copy of this letter for your records.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

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Appendix B Digital Information Sheet (consent form) for professionals

For IRB Use Only

APPROVED
NOV 24 2014
EXPIRES 11-23-15
PURDUE UNIVERSITY
INSTITUTIONAL REVIEW BOARD

DIGITAL INFORMATION SHEET FOR PROFESSIONALS

Identifying variation in ways to deal with problems in complex systems

Monica E. Cardella, Ph.D
John Mendoza-Garcia, MSEC
School of Engineering Education
Purdue University

What is the purpose of this study?

The purpose of this study is to investigate the variation in ways to deal with problems in complex systems. These variations will give us information that could be used to design tools to assess the ability to respond effectively to this kind of problems; and to develop modules, courses, assignments and programs that may improve it. Improving assessment and curricula in this area is especially important as preparing engineering students to face the problems in the complex systems that will surround them in their professional practice. In this study we are recruiting you because we need to create a "pool" of ways of dealing with problems in complex systems. We want to recruit you because your studies and life experiences may give us one or more ways of dealing with these kinds of problems that will be collected in the pool of ways. We will try to find how your ways and other participant's ways are similar and how they are different from each other. We will interview 20-35 people among undergraduate students of Science, Engineering, Technology, Math (STEM) and management, and professionals with different background and experiences dealing with problems in complex systems.

What will I do if I choose to be in this study?

Your participation in this study will consist of two phases. In the first phase, you will be asked to respond to two tasks or problems in complex systems. You will be interviewed in a private place where you can feel free to talk and express your inner thoughts. In case the interview is conducted by phone, Skype, Google hangouts or any other computer assisted technology, the interviewer (John Mendoza-Garcia) will use speakers only if he is alone and in a private space. In general, the interviewer will use headphones to ensure that no one else can hear your answers.

The interview will be recorded and transcribed verbatim. Regarding your notes from the interview:

- If your interview is face to face, they will be collected, digitalized and attached to the transcript. Any digital file created by you to address the task will be sent by e-mail to the interviewer's e-mail address: mendozag@purdue.edu
- If your interview is by Skype, Google hangouts or by phone, you will scan or take pictures of your notes and you will send these pictures to the interviewer's e-mail address: mendozag@purdue.edu. Any digital file you create to address the task will be sent as well to the interviewer to his e-mail address.

In any of the cases mentioned above, your notes will be included in the study to provide more evidence of the ways in which you deal with problems in complex systems.

After the interview, you will be asked to complete a survey that the researchers will use to make sure that they talk to a rich variety of people with different backgrounds and experiences dealing with problems in complex systems. Accordingly, this survey will ask you about your professional experience, your academic training and will ask you general demographic questions. In case one or more questions either in the survey or during the interview makes you feel uncomfortable, you can skip the question and continue with the next one.

How long will I be in the study?
Pilot studies have shown that typically the time for the interview is 60 minutes, but sometimes it could be expanded up to 90 minutes. Answering the survey will take you between 15 to 30 minutes.

What are the possible risks or discomforts?
There is minimal risk for participants taking this research that is no greater than every day activities. However, breach of confidentiality is a risk and the safeguards used to minimize this risk can be found in the confidentiality section. There is also a risk that some questions in the survey or in the interview may make you feel uncomfortable, in that case you can skip the question and continue with the next one.

Are there any potential benefits?
There are no direct benefits to you. However, through this study the researchers may learn about the development of the ability to deal with problems in complex systems. This new knowledge could be used by them or by other educators to create new tools to assess this ability in existent activities, courses and programs that intends to promote it. Likewise, the results of this study may be used to develop new curricular interventions that use current learning theories as their framework.

Will I receive payment or other incentive?
You will not receive any payment or other incentive for participating in this study

Will information about me and my participation be kept confidential?
The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. To protect identifiable information, the researchers will:
[1] Use aliases and/or codes instead of your identifiable information. Only the principal investigator, the co-investigators and the key-personal would have access to your identifiable information. In case a possible conflict of interests arises between you and one member of the research team different than the graduate student, that member will not know your real identity. The researchers will keep a separated file that links the alias/code to your identifiable information. The file will be protected by using a password. This file will be located in a password protected drive. This drive will be different from the drive in which the data collected is located.
[2] Your identifiable information will be removed from the data collected in the survey and from the transcripts of the interview and replaced with aliases or codes.
The file that links your identifiable information with the alias, and the audio records will be erased by December 2016. The data, stripped of all identifying information will be kept indefinitely and will be disseminated in research reports and presentations.

What are my rights if I take part in this study?
your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty. your decision of participating or not in this study will have no effect on your current relationship with the researchers or with Purdue University. If you choose to withdraw your participation you can contact John Mendoza-Garcia at mendozag@purdue.edu.

Who can I contact if I have questions about the study?
If you have questions, comments or concerns about this research project, you can talk to one of the researchers. The first person to contact will be the interviewer (John Mendoza-Garcia). His e-mail address is

mendozag@purdue.edu and his telephone number is 765-3910102. You may also contact Professor Monica Cardella at cardella@purdue.edu who is the PI for this study; however, the graduate researcher is the primary point of contact.

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, you can call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.,
West Lafayette, IN 47907-2114

Documentation of Informed Consent

I am over 18 years old. I have had the opportunity to read this digital information sheet and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above

☐ I agree

you have large tables or figures to include and need to use margin space, use the right margin and bottom margin.

Appendix C Digital Information Sheet (consent form) for professionals

For IRB Use Only
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NOV 24 2014
EXPIRES 11-23-15
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DIGITAL INFORMATION SHEET FOR PROFESSIONALS

Identifying variation in ways to deal with problems in complex systems

Monica E. Cardella, Ph.D
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Purdue University

What is the purpose of this study?

The purpose of this study is to investigate the variation in ways to deal with problems in complex systems. These variations will give us information that could be used to design tools to assess the ability to respond effectively to this kind of problems; and to develop modules, courses, assignments and programs that may improve it. Improving assessment and curricula in this area is especially important as preparing engineering students to face the problems in the complex systems that will surround them in their professional practice. In this study we are recruiting you because we need to create a "pool" of ways of dealing with problems in complex systems. We want to recruit you because your studies and life experiences may give us one or more ways of dealing with these kinds of problems that will be collected in the pool of ways. We will try to find how your ways and other participant's ways are similar and how they are different from each other. We will interview 20-35 people among undergraduate students of Science, Engineering, Technology, Math (STEM) and management, and professionals with different background and experiences dealing with problems in complex systems.

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The interview will be recorded and transcribed verbatim. Regarding your notes from the interview:

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- If your interview is by Skype, Google hangouts or by phone, you will scan or take pictures of your notes and you will send these pictures to the interviewer's e-mail address: mendozag@purdue.edu. Any digital file you create to address the task will be sent as well to the interviewer to his e-mail address.

In any of the cases mentioned above, your notes will be included in the study to provide more evidence of the ways in which you deal with problems in complex systems.

After the interview, you will be asked to complete a survey that the researchers will use to make sure that they talk to a rich variety of people with different backgrounds and experiences dealing with problems in complex systems. Accordingly, this survey will ask you about your professional experience, your academic training and will ask you general demographic questions. In case one or more questions either in the survey or during the interview makes you feel uncomfortable, you can skip the question and continue with the next one.

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What are the possible risks or discomforts?
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Are there any potential benefits?
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Will information about me and my participation be kept confidential?
The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. To protect identifiable information, the researchers will:
[1] Use aliases and/or codes instead of your identifiable information. Only the principal investigator, the co-investigators and the key-personal would have access to your identifiable information. In case a possible conflict of interests arises between you and one member of the research team different than the graduate student, that member will not know your real identity. The researchers will keep a separated file that links the alias/code to your identifiable information. The file will be protected by using a password. This file will be located in a password protected drive. This drive will be different from the drive in which the data collected is located.
[2] Your identifiable information will be removed from the data collected in the survey and from the transcripts of the interview and replaced with aliases or codes.
The file that links your identifiable information with the alias, and the audio records will be erased by December 2016. The data, stripped of all identifying information will be kept indefinitely and will be disseminated in research reports and presentations.

What are my rights if I take part in this study?
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☐ I agree

you have large tables or figures to include and need to use margin space, use the right margin and bottom margin.

Appendix D Survey to Capture Variation Among Students

IDENTIFYING THE VARIATION IN WAYS TO DEAL WITH PROBLEMS IN COMPLEX SYSTEMS

** This survey will be uploaded to Qualtrics.

Contact information

Full Name:
e-mail address(es):
Telephone number(s):

Educational background and experiences

1. What is your major (no acronyms please)?
2. What is your classification? (Are you a freshman, a sophomore, etc.)
3. How many semesters have you completed as a college student?
4. Have you ever taken courses that mentioned/covered one or more of the following topics? Y/N
    a. Systems dynamics
    b. Systems thinking
    c. Complex system
    d. Whole systems design
    e. Sustainable design
    f. Organizational system
    g. Technical system
    h. Natural system
    i. Flows, stocks, delays.
    j. None
5. In case you did, list the courses and/or write the number of courses you took.

    ____
6. Did you take primary middle or high school years outside of the US? Y/N
7. In case yes, Please describe (e.g. how many years and which ones)

    ____

8. Were you involved in extra-curricular activities in high school? Y/N
    In case yes, Please describe the activity, the time you were involved and your roles.

    ____
    ____

Experience with problems in Complex Systems

Please answer the following questions to help us understand your experiences dealing with problems in complex systems

9. Which of the following statements fits best according to your current academic and extracurricular experiences, and also is a need to be truth for you to succeed in your curricular and/or extra-curricular experiences?

a. I don't need to be aware of any complex system
(if you are aware, but don't need it to be successful in your studies or in your extra-curricular projects, please mark this option).
b. I need to be aware of the existence of one or more complex systems.
c. I need to understand one or more complex systems.
(For example, to predict the weather a meteorologist needs to know how low air pressure systems interact with high air pressure systems).
d. I need to understand and intervene in complex systems
(The following examples are related to people in decision making positions. However, if you feel that your professional success requires you to understand and intervene in complex systems, please mark this box.
This box may be marked by someone who is the leader of a student's organization and has to make decisions about the kind of activities they will do during the year; or by the leader of a team that is designing a low cost device that transforms Eolic energy into electrical energy to be used the houses of a town that is located on the top of a mountain).

10. Have you ever been involved in understanding a problem in a complex system?

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree	6. I don't understand

11. Have you ever been involved in understanding and solving a problem in a complex system?

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree	6. I don't understand

12. Briefly describe three problems in complex systems you have being involved and describe your role

____

____

13. Have you ever been involved in one or more of these activities? For how long:

a. Community projects where you need to apply your disciplinary knowledge (e.g Engineering)? (For example: EPICS, Social internship, community informatics)

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree

Position (role): ________ ___ # semesters: ________ # projects: _____
Grade how much you agree with the following statement: I needed a lot of creativity and had freedom to do my tasks:

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree

b. Global Engineering Program or Engineers without borders or something similar Y/N___
Position: ________ _______#semesters___________ #Projects: ___
Grade how much you agree with the following statement: I needed a lot of creativity and had freedom to do my tasks:

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree

c. Community service (No use of your discipline related knowledge) Y/N _______
Position: ________ _______#semesters___________ #Projects: ____________
Grade how much you agree with the following statement: I needed a lot of creativity and had freedom to do my tasks:

1. Strongly disagree	2. Disagree	3. Neutral	4. Agree	5. Strongly agree

d. Professional internships Y/N
Position: ________ _______#semesters___________ #Projects: ___
From 1 to 5, grade the creativity and freedom you needed to do your tasks: _____

e. Jobs related with your field of study at the University or school (e.g. peer teacher)
Position: ________ _______#semesters___________ #of different roles: ____________

f. Jobs not related with your field of study but in the University or school (e.g. Work as Resident Assistant in one of the Residence halls)
Position: ________ _______#semesters___________ #of different roles: ____________
From 1 to 5, grade the creativity and freedom you needed to do your tasks: ________

g. Jobs not related with your field of study and outside school Y/N (e.g. waiter).
Position: ________ _______#semesters___________ #of different roles: ____________
From 1 to 5, grade the creativity and freedom you needed to do your tasks: ________

Demographic Information

The following information will help us to ensure that our study population is representative of the general population. Please check the appropriate boxes for the following questions.

Are you: ☐ Male ☐ Female ☐ I prefer to not answer

Please check all categories that accurately represent your race, origin or descent:

☐ White or European-American
☐ Black, African-American or Afro-American
☐ American Indian, Aleut, or Eskimo
☐ Asian or Pacific Islander
☐ Hispanic/Latino
☐ Other ________________
☐ I prefer to not answer

What is your age? ☐ 18-19 ☐20-21 ☐ 22-23 ☐ 24-25
☐ 25 or more ☐ I prefer to not answer

Appendix E Survey to Capture Variation Among Professionals

IDENTIFYING THE VARIATION IN WAYS TO DEAL WITH PROBLEMS IN COMPLEX SYSTEMS.

** This survey will be uploaded to Qualtrics.

Contact information

1. Full name: ___________________________________
2. Telephone number(s): ________________________________
3. E-mail address(es): ____

Background information

Please answer the following questions regarding your professional and academic background

1. What discipline(s) do you most associate yourself with?
2. How many years of professional experience do you have in this discipline?
3. Did you complete primary, middle or high school years outside of the US? Y/N

____

In case yes, Please describe (e.g. how many years and which ones)

4. Have you received a Bachelor's degree? Y/N

__________________ ____

Year Major (s)

____

Country

5. Have you completed a M.S. or PhD? Yes/No

__________________ ____

Master's Discipline Country

__________________ ____

PhD's Discipline Country

6. Have you ever taken courses that mentioned/covered one or more of the following topics?
    a. Systems dynamics
    b. Systems thinking
    c. Complex system
    d. Whole systems design

e. Sustainable design
f. Organizational system
g. Technical system
h. Natural system
i. Flows, stocks, delays.
j. None

7. In case you did, list the courses and/or at least write the number of courses you took.
8. Are you currently pursuing a degree?

________________ ________________________________

# of Years you have taken Discipline

________________ ________________________

Level? Master, PhD? Country

Experience with problems in Complex Systems

Please answer the following questions to help us understand your familiarity with problems in complex systems

9. Which of the following statements fits best according to your current professional experience and practice, and it needs to be truth for you to succeed in your professional practice?:
   a. I don't need to be aware of any complex system

(if you are aware, but don't need it to be successful in your job or in your professional practice in general, please mark this option).

   b. I need to be aware of the existence of one or more complex systems.
   c. I need to understand one or more complex systems.
   d. (For example, To predict the weather a meteorologist needs to know how low air pressure systems interact with high air pressure systems).
   e. I need to understand and intervene in complex systems.

(The following examples are related to people in decision making positions. However, if you don't identify any resemblance between what you do and the roles described here, but you consider that your professional success requires you to understand and intervene in complex systems, please mark this box.
This box may be marked by someone who is the leader of a team that is developing a new information system that manages the medical records of a hospital; or by someone who is leading the design of a device that purifies water

for a community in an underdeveloped country with low access to potable water; or by the leader of a team that is designing a more energy effective car to be used in the desert; or by the leader of a team that is designing the rotor blade for a new helicopter; or by the manager or organizational leader that defines new policies or strategies that are followed by a unit or a company, etc.)

10. How many companies have you worked for?
11. For how many of these were you involved in problems that were related to complex systems?
12. Briefly describe three problems in complex systems you have been involved and describe your role.

____
____
____
____
____
____

13. In the section below, we ask for information about the last three companies you have worked for. The information is for descriptive purposes only; we will not contact individuals at these companies.

Company one: Current Company

Current Position at the company: ___________________

Grade how much you agree with the following sentences

In my current position my company supports and promotes creativity.

7. Strongly disagree	8. Disagree	9. Neither disagree nor agree	10. Agree	11. Strongly agree

My company create spaces or activities to be able to understand better how the company works, how do I contribute to its mission, and how other departments are related to mine.

12. Strongly disagree	13. Disagree	14. Neither disagree nor agree	15. Agree	16. Strongly agree

Number of different roles or positions you have had in this company

____

Name of company:_____________________________

What is the size of this organization? ☐ 1-19 employees ☐ 20-99 employees ☐ 100-499 employees ☐ 500-9,999 employees ☐ 10,000 or more employees	How would you describe this organization? (check all that apply) ☐ Education ☐ Public ☐ Non-profit ☐ Manufacturing ☐ Market Development	How many problems in complex systems have you contributed to address while working with this organization? ☐ 0-2 ☐ 3-5 ☐ 6-10 ☐ More than 10
Which aspects of addressing problems in complex system have you been involved in? (check all that apply) ☐ Problem definition ☐ Conceptual solution ☐ Detailed Solution ☐ Implementation ☐ Other: - _____________	What roles have you played at this organization? (check all that apply) ☐ Faculty ☐ Technical Expert ☐ Lead Engineer ☐ Project Manager ☐ Other: ____________	How long have you worked with this organization? ☐ Less than 1 year ☐ 1-3 years ☐ 3-5 years ☐ 6-10 years ☐ More than 10 years

Position Two: Previous Company
Last position at the company: ___________________________
From 1 to 5, how much this company supported and promoted creativity in that position?

____
Number of different roles or positions you had in this company

____
Name of Company:____________________________

What is the size of this organization? ☐ 1-19 employees ☐ 20-99 employees ☐ 100-499 employees	How would you describe this organization? (check all that apply) ☐ Education ☐ Public	How many problems in complex systems have you contributed to address while working with this organization?

☐ 500-9,999 employees ☐ 10,000 or more employees	☐ Non-profit ☐ Manufacturing ☐ Market Development	☐ 0-2 ☐ 3-5 ☐ 6-10 ☐ More than 10
Which aspects of addressing problems in complex system have you been involved in? (check all that apply) ☐ Problem definition ☐ Conceptual solution ☐ Detailed Solution ☐ Implementation ☐ Other: - ______________	What roles have you played at this organization? (check all that apply) ☐ Faculty ☐ Technical Expert ☐ Lead Engineer ☐ Project Manager ☐ Other: _____________	How long have you worked with this organization? ☐ Less than 1 year ☐ 1-3 years ☐ 3-5 years ☐ 6-10 years ☐ More than 10 years

Company three: Previous Company

Last position at the company: _____________________________

From 1 to 5, how much that company supported and promoted creativity for that position?

____

Number of different roles or positions you had in this company

____

Name of Company:______________________________

What is the size of this organization? ☐ 1-19 employees ☐ 20-99 employees ☐ 100-499 employees ☐ 500-9,999 employees ☐ 10,000 or more employees	How would you describe this organization? (check all that apply) ☐ Education ☐ Public ☐ Non-profit ☐ Manufacturing ☐ Market Development	How many problems in complex systems have you contributed to address while working with this Organization? ☐ 0-2 ☐ 3-5 ☐ 6-10 ☐ More than 10

Which aspects of addressing problems in complex system have you been involved in? (check all that apply)	What roles have you played at this organization? (check all that apply)	How long have you worked with this organization?
☐ Problem definition	☐ Faculty	☐ Less than 1 year
☐ Conceptual solution	☐ Technical Expert	☐ 1-3 years
☐ Detailed Solution	☐ Lead Engineer	☐ 3-5 years
☐ Implementation	☐ Project Manager	☐ 6-10 years
☐ Other: - ______________	☐ Other: _____________	☐ More than 10 years

14. Have you been involved in a project with the goal of dealing with a problem in a complex system that included team members with the following expertise?

☐ Aeronautical Engineering
☐ Astronautical Engineering
☐ Biomedical Engineering
☐ Ceramic Engineering
☐ Chemical Engineering
☐ Civil Engineering
☐ Computer Engineering
☐ Electrical Engineering
☐ Electronic engineering
☐ Environmental Engineering
☐ Forest Engineering
☐ Hardware Engineering
☐ Industrial Engineering
☐ Materials Engineering
☐ Manufacturing Engineering
☐ Mechanical Engineering
☐ Nuclear Engineering
☐ Operations Engineering
☐ Quality Engineering
☐ Software Engineering
☐ Structural Engineering
☐ Systems Engineering
☐ Transportation Engineering
☐ Other:_____________________

15. Have you been involved in involved in a project with the goal of dealing with a problem in a complex system that included team members with the following expertise?

☐ Accounting
☐ Anthropology

- ☐ Applied Mathematics
- ☐ Architecture
- ☐ Artist
- ☐ Atmosphere Sciences

- ☐ Biochemistry
- ☐ Biology
- ☐ Business
- ☐ CAD Designer
- ☐ Chemistry
- ☐ Computer Science
- ☐ Economics
- ☐ Education
- ☐ Electrician
- ☐ Finance
- ☐ Geology
- ☐ Graphic Design
- ☐ History
- ☐ Human Resources
- ☐ Industrial Design
- ☐ Information Systems
- ☐ Landscape Architecture
- ☐ Linguistics
- ☐ Marketing
- ☐ Medicine
- ☐ Physics
- ☐ (Computer) Programming
- ☐ Project Management
- ☐ Psychology
- ☐ Public Affairs
- ☐ Real Estate
- ☐ Sociology
- ☐ Statistics
- ☐ Technical Communication
- ☐ Training
- ☐ Urban Planning
- ☐ Other:______________________

Demographic Information

The following information will help us to ensure that our study population is representative of the general population. Please check the appropriate boxes for the following questions.

Are you: ☐ Male ☐ Female ☐ I prefer to not answer

Please check all categories that accurately represent your race, origin or descent:

- ☐ White or European-American
- ☐ Black, African-American or Afro-American
- ☐ American Indian, Aleut, or Eskimo
- ☐ Asian or Pacific Islander
- ☐ Hispanic/Latino
- ☐ Other _________________
- ☐ I prefer to not answer

What is your age? ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ 61-70 ☐ 71-80

☐ I prefer to not answer

Appendix F IEEE copyright permission to reuse content from an IEEE publication

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Title: Identifying the variation of experiences when dealing with problems in complex systems

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VITA

VITA

John Alexander Mendoza Garcia

Education

PhD	Purdue University (USA)	2016	Engineering Education
MS	Universidad de los Andes (Colombia)	2004	Systems Engineering and Computing
BS	Universidad Nacional de Colombia	1997	Systems Engineering

Professional Experience

Title	School	Dates
Research Assistant	Purdue University	Fall 2015-summer2016
Summer Research Grant Recipient	Purdue University	Summer 2015
Future Faculty Fellow in the First Year Engineering Program	Purdue University	Fall 2013- spring 2015
Research Assistant	Purdue University	Fall 2011-Summer 2013
Assistant Professor	Pontificia Universidad Javeriana	Jan 2009 – Summer 2016
Instructor Professor	Pontificia Universidad Javeriana	Aug 2005 – Dic 2008
Adjunct professor	Universidad Católica de Colombia	Aug 2004- Aug 2005
Lecturer	Universidad de la Salle	Aug 2004 – Dic 2005

Memberships

Board, Academic Forum. Systems Engineering for all Engineers. International Council for Systems Engineering INCOSE (2016 -)
Member, American Society for Engineering Education (2011-)
.

Honors and Awards

Purdue University. College of Engineering. Graduate School. Summer Research Grant. June-August 2015.

Bisland dissertation fellowship. 2014. Program Nominee.

Outstanding paper award honorable mention. American Society of Engineering Education. Illinois / Indiana Sectional conference. Valparaiso, IN. March 17, 2012.

Colciencias. National Grant for doctoral studies year 2012 (No.568).

Colfuturo. Recipient of a forgivable credit. 2011.

Honors Degree. Magister en Ingeniería de Sistemas y Computación. Universidad de los Andes. Bogotá. 2004.

Unisys Colombia: Recognition for accomplishing the Branch Solution Project's objectives with excellent quality and on time. Bogotá. 1997.

Reviewer / Session Moderator service

American Society for Engineering Education (2012-)

Frontiers in Education (2013 -) Session moderator as needed

Grant Writing Experience

As primary author

National science Foundation – REES Division. Project title. Identifying the variation in ways to deal with problems in complex systems. PI. Dr. Monica Cardella. 2014. $50.000. Not Awarded.

Systems Engineering Research Center. Project title: Developing an empirical framework for characterizing levels of systems thinking. PI. Dr. Monica Cardella. 2014. $20.000. Not awarded.

National Academy of Education/Spencer dissertation fellowship program in education research. 2014. $55.000. Not awarded.

Purdue Graduate Student Government – PGSG. Child grant. Fall 2015. Support for day care / pre-school of graduate students children. $1000. Awarded.

Purdue Graduate Student Government – PGSG. General research grant. Fall 2015. Support for various activities related to dissertation work. In my case, I asked for funding for the payment of transcriptions. $500. Awarded.

Purdue Graduate School – Span Plan Adult student services. Cecelia Zissis Graduate Student Scholarship recipient, Spring 2015. Support for tuition of fall 2015 and spring 2016 for non-traditional students. $1000. Awarded.

College of Engineering, Travel Grant. Fall 2014. Support for attendance to a conference. I used it to attend Frontiers in Education Conference 2014. $500. Awarded.

As team member

Departamento Administrativo de Ciencia y Tecnología e innovación - Colciencias (Administrative Department of Science, Technology and Innovation). Project title: AYLLU: Cooperation platform mediated by agents applied to a collaborative E-learning context (Original title: Plataforma de Cooperación mediada por agentes aplicada en un Contexto de E-learning Colaborativo). PI. Enrique Gonzalez Guerrero. 2010. Awarded.

PUBLICATIONS

PUBLICATIONS

PEER REVIEWED CONFERENCE PAPERS.

Liu, G., Tolbert, D., **Mendoza-Garcia, J.**, Roshan-Sriram, A. Cardella, M. Quantitative Information Acquisition and Utilization for First-Year Engineering Students. Abstract approved. ASEE, 2016.

Taleyarkhan, M., **Mendoza-Garcia, J**., Magana, A. Investigating the impact of an educational CAD modeling tool on student design thinking. Abstract approved. ASEE, 2016.

Dringenberg, E., **Mendoza-Garcia J**., Tafur, M., Fila, N, Hsu, M**.** (2015) Using Phenomenography: What are Key Considerations when Selecting a Specific Research Approach. Available at: https://peer.asee.org/25012

Presenter. Mendoza-Garcia J., Cardella M., Oakes W. (2014). Various ways of experiencing dealing with complex problems. Frontiers in Education. Madrid, España. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7044347&tag=1

Presenter. Mendoza-Garcia J., Cardella M. (2014). Using Alien-Centered Design for teaching iteration in the design process in undergraduate design courses. Madrid, España.

Presenter. Mendoza-Garcia J., Cardella M., Zoltowski C., Oakes, W. (2013). Understanding the motivation of instructors to get involved in service learning environments. Frontiers in Education. Oklahoma city, OK. Available at: http://www.computer.org/csdl/proceedings/fie/2013/9999/00/06684951-abs.html

Presenter. Mendoza-Garcia, J. (2013). Developing an instrument to assess student's prior knowledge and possible interest in Public Policy courses. American society for Engineering Education. National conference. Atlanta, GA. Available at: http://www.asee.org/public/conferences/20/papers/6822/view

Presenter. Mendoza-Garcia, J. (2013). Identifying reflective practice in one engineering design meeting. American Society for Engineering Education Ilinois / Indiana Sectional conference. Angola, IN. Available at: http://ilin.asee.org/2013/index_files/papers-full.html

Presenter. Mendoza-Garcia, J., Ngambeki, I., Behbehani, L., Evangelou, D., Rao, S. Cox, M. (2012). Defining the knowledge and skills that enable Engineers to participate in public policy. American Society for Engineering Education. National Conference. San Antonio, TX. June, 2012. Available at: http://www.asee.org/public/conferences/8/papers/4262/view

Presenter. Mendoza-Garcia, J., Grundman, L., Wang, J., Purzer, S. (2012). Students' modeling through visual and verbal representations. American Society for Engineering Education Ilinois / Indiana Sectional conference. Valparaiso, IN.
Available at: http://ilin.asee.org/Conference2012/ASEE_ILIN_2012_Proceedings.html

Presenter. Mendoza-Garcia, J., Ngambeki, I., Behbehani, L., Evangelou, D., Rao, S. Cox, M. (2012). Literature review of the knowledge and skills that enable engineers to participate in public policy. IL/IN Sectional conference. Valparaiso, IN. Available at: http://ilin.asee.org/Conference2012/ASEE_ILIN_2012_Proceedings.html

Fiorillo, G. **Mendoza-Garcia J,** Fajardo S, Dorado R, Acevedo J, Perez BC. (2010) Engineering for sustainable development. University and Society Alliance. Case of study: Amparo Foundation. Annual meeting of engineering faculties – ACOFI. Santa Marta. Colombia 2010. Original Title: La ingeniería para el desarrollo regional sostenible: Alianza Universidad y Sociedad. Caso de estudio Fundación Amparo.

Gomez A., **Mendoza-Garcia J**., Fiorillo G., Acevedo J., Perez B. (2009). Social Project based learning. An strategy to perform Social Responsibility at the University. Annual meeting of engineering faculties – ACOFI. Santa Marta. Colombia P. 173. ISBN: 978-958-680-062-4. Original Title: Aprendizaje Basado en Proyectos Sociales: Estrategia para ejercer Responsabilidad Social Universitaria.

Presenter. Mendoza-Garcia J. (2008). A proposal for Social Internships from Systems Engineering. Annual meeting of engineers faculties - ACOFI. Cartagena, Colombia.. P.57. ISBN: 978-958-680-058-7 Original title: Una Propuesta de Prácticas Sociales desde Ingeniería de Sistemas. Reunión Nacional de Facultades de Ingeniería - ACOFI. Cartagena, Colombia. 2008.

Presenter. Mendoza-Garcia J. (2007b). **UE Alliance: Creating learning environments between University and industry**. III meeting of Professional Internships. University of the North. Barranquilla, Colombia. 2007. Original title: Alianza UE: Generando espacios de Aprendizaje entre la Universidad y la Empresa. III Encuentro Nacional de Prácticas Profesionales. Universidad del Norte. Barranquilla. 2007.

Presenter. Mendoza-Garcia J. (2007a) **Critical Analysis of the change management process in the graduation projects at the Systems Engineering Program. Learned lessons.** II meeting of Systemic Latinoamerican practices. Latinoamerican Systemic Alliance – ALAS. Coruniversitec. Ibagué. Colombia. Original title: Análisis Crítico del Manejo del Cambio en el Proceso de Trabajos de Grado para la Carrera de Ingeniería de Sistemas de la Pontificia Universidad Javeriana. Lecciones aprendidas. II Encuentro de Prácticas Latinoamericanas en Sistémica. Alianza Latinoamericana de Sistémica – ALAS. Coruniversitec. Ibagué